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LARGE SPACE TELESCOPE
ENGINEERING SCALE MODEL
OPTICAL DESIGN

by

Terence A. Facey

April 1973

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Prepared Under Contract No. NAS 8-29312
THE PERKIN-ELMER CORPORATION
Norwalk, Connecticut
for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

PERKIN-ELMER

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FOREWORD

This final report documents and summarizes the detailed optical design analysis of the Large Space Telescope Engineering Scale Model performed for NASA, Marshall Space Flight Center under Contract NAS 8-29312.

The study reviewed various concepts/design configurations and, with MSFC approval (reference Conceptual Design Report, Perkin-Elmer Engineering Report No. 11378), selected a single telescope/relay form for detailed design. Two fine guidance optical concepts have also been designed in detail and integrated with the telescope/relay so that MSFC can evaluate the applicability of each to the LST system. A significant part of the study was devoted to an analysis of the effects of articulation of the secondary mirror. A novel field corrector design has been developed, based upon a Perkin-Elmer adaptation of the Rosin corrector plate. This small, light-weight unit permits correction of astigmatism and field curvature in the guidance field, without need for large diameter, heavy refractive field corrector lenses.

The optical design data is presented in Section III with the overall system tolerance analysis defined in Section IV.

Unless otherwise stated, all dimensions are in millimeters and the wavelength of light is taken as 5, 000Å.

SECTION I

SUMMARY

The overall objective of the Large Space Telescope (LST) Program is the near earth orbiting of a long life 3 meter diffraction-limited telescope system. This system will permit attainment of high resolution imagery, being clear of the degrading effects of the earth's atmosphere and in an environment where the low level of disturbances will allow high pointing stability. The telescope will resolve fainter objects than possible from the earth's surface and will be capable of prolonged operational periods. To attract a large user body, the system will provide a wide selection of instrument types operating over a broad spectral band and output data in a form convenient to astronomers. It will be designed for experimental versatility to allow for expected change in astronomy interest over its long lifetime and to take full advantage of the space shuttle system.

The LST Engineering Scale Model will serve as the ground-based test bench for the testing and evaluation of critical subsystems and the development of technology required for LST. The size/capability of LST will place special demands on system pointing and stabilization, optical wavefront measurement, system inflight alignment, mirror figure control and thermal control of the optical structure.

The objective of this study is to develop the detailed design and tolerance data for the LST Engineering Scale Model optical system. This will enable MSFC to move forward to the optical element procurement phase and also to evaluate tolerances, manufacturing requirements, assembly/checkout procedures, reliability, operational complexity, stability requirements of the structure and thermal system and the flexibility to change and growth.

1.1 REQUIREMENTS

The baseline telescope defined for this study was a 1.2-meter, f/2.2 primary mirror Ritchey-Chretien form with a system speed of f/12. All data optics were to be reflective. The diffraction-limited system was to produce a 5 $\widehat{\text{min}}$ data field at f/12 and a 2 $\widehat{\text{min}}$ data field at f/96 with a data field wavefront error of less than $\lambda/10$ rms. Fine image stabilization was to be achieved by articulating the secondary mirror sufficient to compensate for ±2 $\widehat{\text{sec}}$ motion of the telescope line of sight. The design was to be modular in form with four optically independent elements: telescope, relay, fine guidance optics and coarse acquisition optics. Two telescope system designs, with differing tracking schemes, were defined by the study.

1.2 TELESCOPE SYSTEM WITH IMAGE MOVER

This optical system and its principal dimensions are shown in Figure 1. The Ritchey-Chrétien (R/C) telescope objective produces a diffraction-limited 5 $\widehat{\text{min}}$ diameter data field at the f/12 focal plane. The central 2 $\widehat{\text{min}}$ of the field are relayed by the off-axis, reflective eight power data relay to the data sensor located in the f/96 image plane.

Diffraction-limited performance at f/96 can be achieved, of course, only if the image can be held stable to within about 0.008 $\widehat{\text{sec}}$ of motion or jitter during an exposure. To achieve this performance requirement, offset tracking methods are used. Guide stars, located in the 18 $\widehat{\text{min}}$ to 36 $\widehat{\text{min}}$ diameter circular guidance field of the R/C are passed through pairs of Rosin plate correctors. These adjustable corrector plates will correct the off-axis astigmatism and field curvature present in the field of the R/C design. The corrected guide star image is relocated by the optical image mover to a fixed point just outside the 2 $\widehat{\text{min}}$ data field. In this way the necessarily large field of view required to obtain the needed guide stars can be provided and then, without scale change, the guide star moved closer to the data star so that common, smaller, following optical elements can relay both stars. In this design the diameter of the 2 $\widehat{\text{min}}$ field at f/12 is 8.37 mm and the image mover brings any guide star located within the 36 $\widehat{\text{min}}$ (150 mm) diameter field into a point 6 mm off-axis at f/12, so that it is readily relayed by the following data relay system. Detailed descriptions of the Rosin corrector plates and the image mover are given in Section III of this report.

There are three basic sources of guidance error attributable to the telescope system during an exposure period:

- Movement of telescope line of sight
- Movement of data instrument due to thermal or dynamic load on support structure
- Movement of the eight power relay or any of its elements

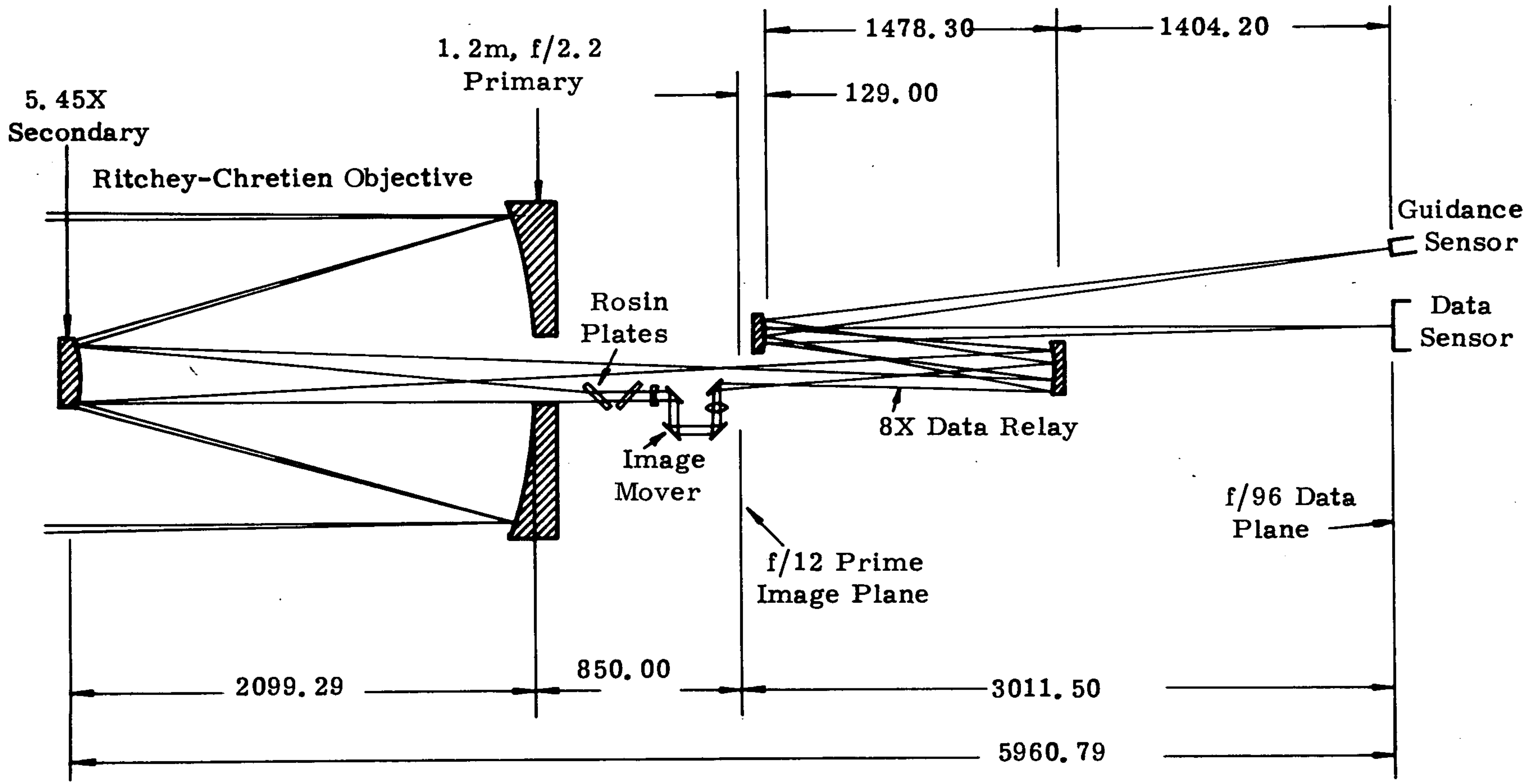

Figure 1. Ritchey-Chretien General Arrangement

The key element of the image mover design is that it provides common optical paths for both the data star and guide star. The guidance sensor, located in close proximity to the data sensor at f/96 can thus sense any of the above motions and provide the correction signal to the articulated secondary mirror. Table 1 gives the key tolerance requirements for the telescope/guidance system design. The structural stability requirements are inherently less demanding, being determined by criteria of optical focus and alignment and not by the stringent requirements of allowed jitter (0.008 $\widehat{sec}$) than would result if data sensor and guidance sensor were significantly separated and the intervening structure required to hold a true dimension.

The image mover/Rosin plate combination will require a drive to position it in the field at the selected guide star. Any drive presents operational and reliability problems but all concepts so far suggested for LST have in one form or another, to provide a drive to meet this condition. Tolerances on the absolute position of the image mover are dependent upon the accuracy to which coordinates of guide star and telescope true line of sight are known. Knowing these coordinates, the image mover must be positioned so that the guide star falls within its 30 $\widehat{sec}$ field.

Because the optical relay will be relaying both data star and guidance star (and they may often differ considerably in magnitude) it will be important in this design that the optical surfaces in the relay system be extremely low in scatter characteristics.

TABLE 1. ALIGNMENT STABILITY TOLERANCE DATA TELESCOPE SYSTEM WITH IMAGE MOVER

Ritchey-Chrétien secondary decentration	±0.5 mm
Relay module decentration	±12μ
Relay module tilt	1.5 $\widehat{sec}$
Relay primary mirror decentration	10μ
Relay primary mirror tilt	1-0 $\widehat{sec}$
Image mover position	±0.5μ
Rosin plate angles	±0.02°
Structure (image plane) motion	±0.1 mm

1.3 TELESCOPE SYSTEM WITH F/12 GUIDANCE

This optical system is shown in Figure 2. The Ritchey-Chrétien telescope system and eight power data relay are identical to the system just described: they provide a diffraction-limited 5 $\widehat{\text{min}}$ data field at f/12 and a 2 $\widehat{\text{min}}$ data field at f/96. This design must also provide stability of ±0.008 $\widehat{\text{sec}}$ at f/96. As in the initial design just described offset tracking methods are used on the guide stars in the 18 $\widehat{\text{min}}$ to 36 $\widehat{\text{min}}$ diameter annular guidance field. The off-axis guide star is first passed through pairs of Rosin plate correctors which correct off-axis astigmatism and field curvature. This provides a well corrected f/12 guide star image in a flat plane at f/12. The image size at f/12 is only 14 microns in diameter. A small 8X relay is used to enlarge the image prior to its passing into the guidance sensor mounted at f/12.

If no further image motion detection/stabilization is used, two sources of image error at f/96 remain:

- Movement of the instrument support structure between f/12 and f/96 due to thermal or dynamic effects
- Movement of any part of the relay system or its support structure

Table 2 gives the summary optical tolerances for the system and it is apparent that this design approach shifts the burden for good image stabilization into the structural and thermal system design areas. The difficulty of meeting the structural/thermal tolerance requirements will also most certainly increase with size of telescope system and with the internal complexity in number of data instruments, complexity of optical relay systems, quantity of subsystem equipment present and its thermal effects and maintenance/servicing requirements.

An alternate to this system is shown in Figure 3. A small light emitting diode is located in the f/12 image plane close to the edge of the data field of the R/C telescope. In this location (similar to the exit point of the image mover design) the LED can provide an optical link to a guidance sensor located in a fixed position in the f/96 image plane near the data sensor. This 'metering' link then will measure only motions of the instrument support structure and its error signal will provide a correction signal to the prime guidance sensor at f/12. In this way the secondary mirror is the single key image stabilization element and image stabilization is achieved directly to each instrument. The tolerance summary is shown in Table 3.

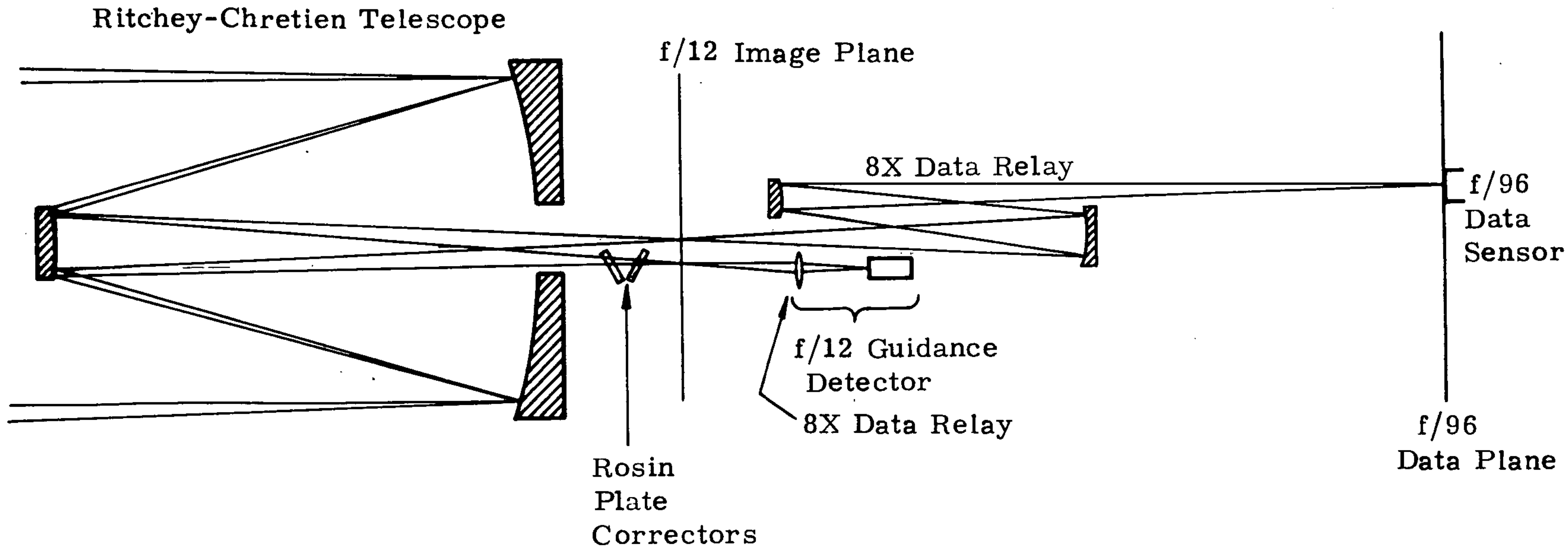

Figure 2. Ritchey-Chretien Telescope with f/12 Guidance Detector

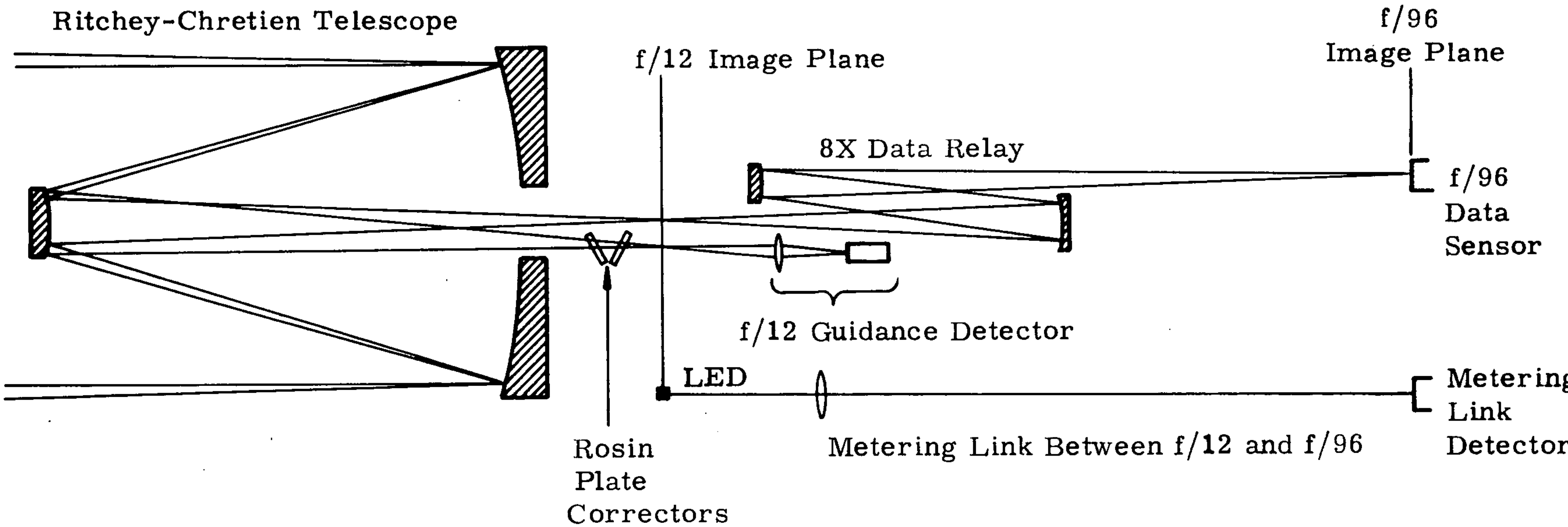

Figure 3. Ritchey-Chretien Telescope with f/12 - f/96 Metering Link

A consideration of this tolerance data shows the system to be highly improbable. Although the metering link will monitor structural flexures between the f/12 and f/96 image planes, it does nothing to alleviate the problems of stability of the relay optical elements.

The only way to monitor optical component stability, as well as overall structural stability, is to meter the system from f/12 to f/96 through the relay lens - just as the data star image does. A separate metering system involving a LED, imaged through the 8X data relay to a detector at f/96 has the general form shown in Figure 4 and tolerances shown in Table 4. It can be seen that this system is very similar to the image mover system depicted in Figure 1 and summarized in Table 1. The LED simply replaces the guide star as a light source in the region behind f/12.

The difference in the two systems centers on the exchange of the optical image mover device for an internal 'star' source and some additional complexity in guidance electronics. There seems no rational alternative for providing a guidance detector directly at the f/96 image plane. Certainly proven flight optical system experience suggests that this is a requirement (and this experience is with considerably less stringent stability requirements). The use of a light source introduces risk of failure. In both systems the problem of light scatter throughout the system must be given careful attention.

TABLE 2. ALIGNMENT STABILITY TOLERANCE DATA F/12 TRACKING

Ritchey-Chretien secondary decentration	±0.5 mm
Relay module decentration	±0.6 μ
Relay module tilt	±0.06 sec
Relay primary mirror decentration	±0.3 μ
Relay primary mirror tilt	±0.04 sec
Structure (image plane) motion	±5 μ

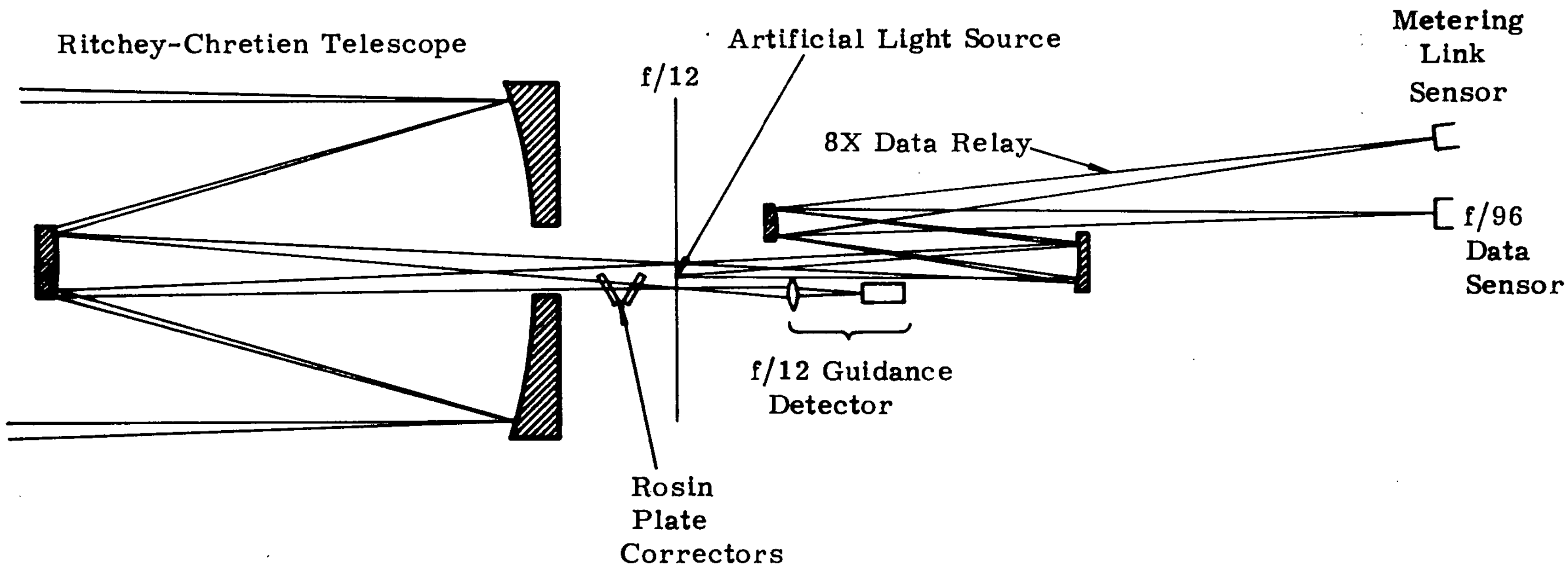

Figure 4. Ritchey-Chretien Telescope with Artificial Light Source

TABLE 3. ALIGNMENT STABILITY TOLERANCE DATA F/12 TRACKING AND SEPARATE METERING LINK TO F/96

Ritchey-Chrétien secondary decentration	±0.5 mm
Relay module decentration	±0.6μ
Relay module tilt	±0.06 sec
Relay primary mirror decentration	±0.3μ
Relay primary mirror tilt	±0.04 sec
Structure (image plane) motion	±0.1 mm

TABLE 4. ALIGNMENT STABILITY TOLERANCE DATA TELESCOPE SYSTEM WITHOUT IMAGE MOVER

Ritchey-Chrétien secondary decentration	±0.5 min
Relay module decentration	±12μ
Relay module tilt	1.5 sec
Relay primary mirror decentration	10μ
Relay primary mirror tilt	1-0 sec
Rosin plate angles	±0.02°
Structure (image plane) motion	±0.1 mm

SECTION II

STUDY DESIGN REQUIREMENTS

The LST Engineering Scale Model system will serve as the key tool for checking and evaluating system and technology innovations required to insure the high performance and long life of the 3 meter Large Space Telescope. MSFC has carefully defined the design parameters and objectives for this optical system design study based on the results of the recently completed LST Phase A study. The requirements define a basic telescope/relay system, two fine guidance concepts, coarse acquisition optics, and a window at the aperture of the telescope.

2.1 TELESCOPE/RELAY

- f/12 Ritchey-Chretien telescope with f/2.2 primary of 1.2 meter diameter
- 8-power all reflecting relay
- Diffraction-limited imaging at both f/12 and f/96 5 $\widehat{\text{min}}$ field at f/12, 2 $\widehat{\text{min}}$ at f/96 wavefront error at f/96 less than $\lambda/10$ rms
- Data sensor at f/96: integrating SEC Vidicon
- 36 $\widehat{\text{min}}$ field of view with wavefront error less than $\lambda/5$ rms
- Diffraction-limited performance and pointing stability as noted with secondary mirror articulated to compensate ±2 arc sec movement of telescope line of sight
- All-reflective design, minimum number of surfaces
- Modular construction; telescope and relay
- Provide back focal space sufficient to accommodate a focal plane figure sensor, spectrograph, automatic focus and filter wheel

- Length not to exceed 6.5 meters, diameter 1.8 meters
- Full aperture window to withstand differential pressure of 1/2 psia maximum.
- Coarse acquisition optics, 2° field of view

2.2 FINE GUIDANCE SYSTEM

- Tracking field from 18 to 36 min. diameter with rms image errors less than $\lambda/5$
- Pointing stability to 0.008 arc-second over the ±2 arc-second allowed telescope movement
- Tracking to utilize 30 arc-second diameter portion of tracking field
- Acquire and track on 12th magnitude star
- Modular construction
- Design need not be all reflecting, should consider reliability

SECTION III

OPTICAL DESIGN DATA

This section contains a description and details of the system optical design. In summary, the basic telescope is of the Ritchey-Chrétien form providing a diffraction-limited 5 $\widehat{\text{min}}$ data field at the f/12 image plane. The central 2 $\widehat{\text{min}}$ of the data field is relayed to f/96 by an all-reflective relay comprised of two off-axis portions of centered conic mirrors. Both relay elements are oblate spheroids. Length available was a key element in the selection of this configuration. Field corrector lenses are not used; instead the instantaneous 30 $\widehat{\text{sec}}$ portion of the guidance field is corrected for astigmatism and field curvature by small flat tilted optical plates. Two fine guidance designs are considered; the first optically relays the guidance star through the entire system to a guidance sensor essentially integral with the data sensor. The second design provides for tracking at f/12 and an auxiliary metering loop to sense any movement of the instrument section of the telescope behind the f/12 plane.

3.1 RITCHEY-CHRÉTIEN TELESCOPE

A pure Ritchey-Chrétien is defined by the four initial parameters:

Dp = primary mirror clear aperture = 1.2m

Fp = primary mirror focal ratio = 2.2

F = telescope system focal ratio = 12

B = vertex back focus, or working distance

The first three of these parameters have been defined by the baseline data upon which this detail design study is based. The only remaining parameter is the vertex back focus distance, B, and for this design it was chosen to be somewhere between 0.8m and 1.0m, in order that sufficient space would be available for later incorporation of fold mirrors and focal plane instrumentation.

The pure Ritchey-Chrétien form is now defined, geometrically (Table 5). A tabulation of the remaining derived parameters follows:

secondary mirror magnification - 5.45

system focal length - 14,400 mm

mirror separation - 2,099.2938 mm

primary mirror curvature - 1.9939410×10^{-4} mm^{-1}

(radius = 5,279.9952 mm)

primary mirror conic constant - 1.731380×10^{-2}

secondary mirror curvature 7.5518867×10^{-4} mm^{-1}

(radius = 1,324.1724 mm)

secondary mirror conic constant -1.25475

vertex back focus 850.0024 mm.

The mirror sags are then defined by $Y(r) = \frac{cr^2}{1 + (1 - Kc^2 r^2)^{1/2}}$ in which c and K are the appropriate curvature and conic constants respectively, for the mirror in question.

Sag for each of the mirrors in the Ritchey-Chrétien are tabulated in Appendices A and B. These tables show, for 150 equispaced points along a mirror radius, the absolute sag from a reference plane containing the vertex and the sub-sag, being the difference between the aspheric mirror surface and a best fit reference sphere containing the vertex.

The telescope system is shown in Figure 5 which also indicates the size of the hole in the primary mirror as being 185 mm minimum diameter. Maximum primary mirror hole size is set by the requirement that it does not introduce a central obscuration greater than that already introduced by the secondary mirror. This sets a maximum hole size at approximately 280 mm diameter. That is, the minimum required clear aperture through the primary mirror hole is 185 mm diameter and the maximum primary mirror central obscuration diameter is 280 mm. The region between these two concentric diameters is available for baffling, mirror mounts, and other mechanical hardware.

In terms of achieving a data field image quality better than $\lambda/10$ rms and a guidance field image quality better than $\lambda/5$ rms, the Ritchey-Chrétien

TABLE 5. RITCHEY-CHRÉTIEN OPTICAL DESIGN

PERKIN-ELMER
OPTICAL OPERATIONS DIVISION
SOUTH WILTON, CONNECTICUT

LENS DESIGN DATA SHEET

SHEET 1 OF 1

SPO/WO.	DATE	RECOMP.	DESIGN NO.
40649/30,100	3/23/73		

EQUIVALENT FOCAL LENGTH		MAGNIFICATION	
APERTURE RATIO	OBJECT SPACE F/: ∞	FIELD AND FORMAT	OBJECT SPACE: 0.3° semi-angular field diam.
	IMAGE SPACE F/: 12		IMAGE SPACE: 150.32 mm diameter
DISTANCES	OBJECT TO IMAGE: ∞	FRONT VERTIX TO BACK VERTEX	2,099.2938
	FRONT VERTEX TO IMAGE: 850.0024	FRONT VERTEX TO ENTRY PUPIL	0.0
	BACK VERTEX TO IMAGE: 2949.2962	BACK VERTEX TO EXIT PUPIL	-503.340154
	FIRST PRINCIPAL POINT: -45658.450987	SECOND PRINCIPAL POINT	-13549.997275
STOP POSITION: At surface #1 - Primary Mirror		STOP SIZE (AT MAX. APERT.)	1199.999974
TRANSMISSION: -		OBSTRUCTION RATIO	0.233
SPECTRAL RANGE: - MED. WAVELENGTH	- MIN. WAVELENGTH	- MAX. WAVELENGTH	

NO.	FIGURE TOL.	SURFACE NO.	CLEAR APERT.	RADIUS	± TOL.	AXIAL DISTANCE	± TOL.	GLASS TYPE	GLASS CODE	GLASS MELT NO.
1	rms λ/64		1,20000. 28010.	-5279.9952 (1)	±5.0	-2,099.2938	±0.1	Mirror		
2	*		268	-1,324.1724 (2)	±1.0	2,949.2962	**	Mirror		
3	-	prime focus	150.32	∞				-		

(1) Primary mirror aspheric - Conic constant is -1.731380.10^-2

(2) Secondary mirror aspheric - Conic constant is -1.25475

* Secondary mirror is figured to give total system performance equal to or better than λ/20 rms OPD

** This distance in the back focus

NOT REPRODUCIBLE

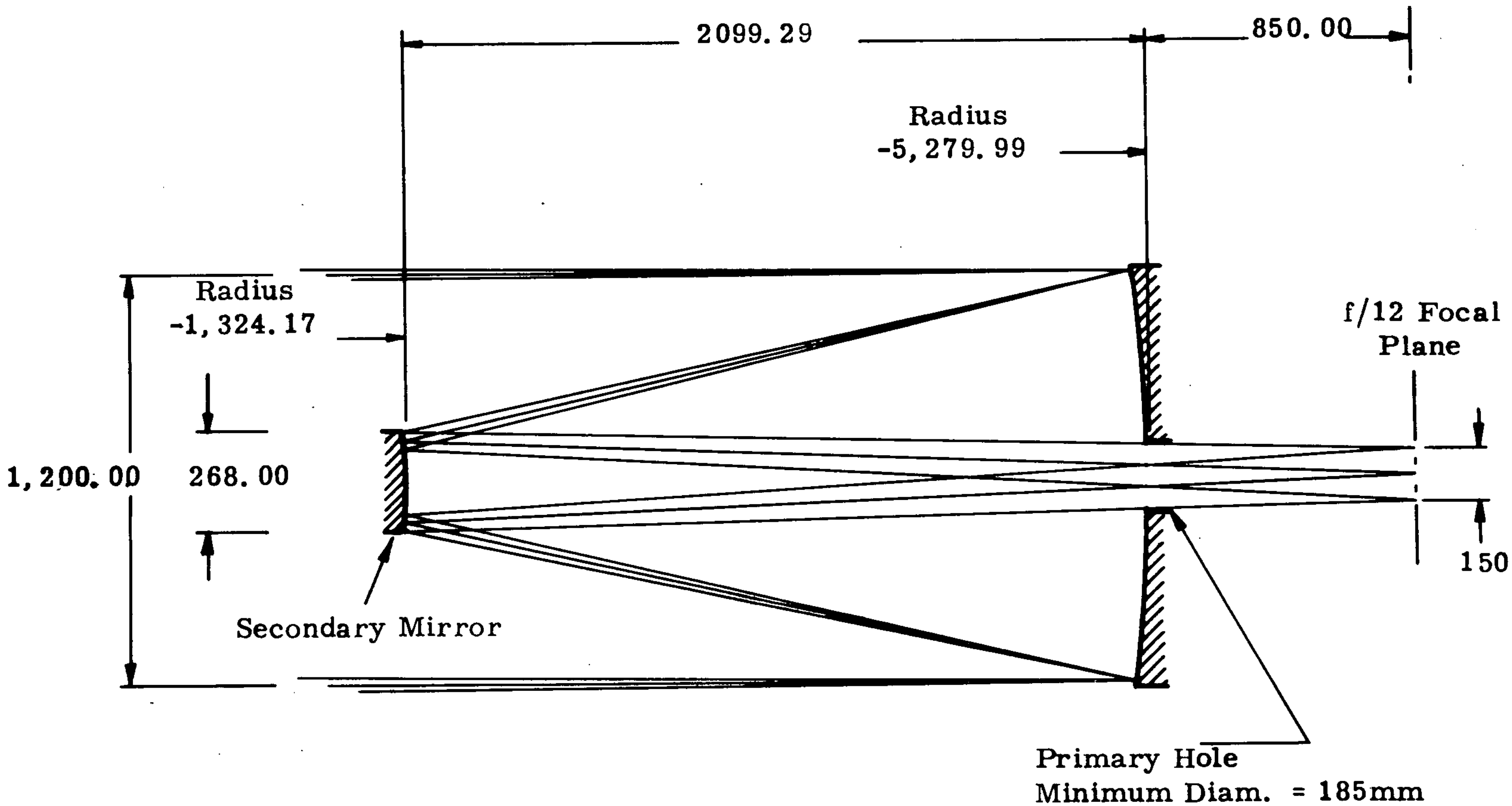

Figure 5, Ritchey-Chretien Ray Trace

telescope system should be figured to provide no more than $\lambda/25$ rms wavefront error over the central 2 $\widehat{min}$ field and no more than $\lambda/15$ rms wavefront error in the 18 $\widehat{min}$ to 36 $\widehat{min}$ annular guidance field.

Aberrations in an optical imaging system are manifest as a spread in the points of intersection of rays from different points in the pupil with the focal plane. Thus, the quality of an optical system may be visualized readily by the lateral aberration curves shown in Figure 6. In these curves, for a given field angle, the ray height at the focal plane is plotted against the pupil radius that ray passes through - normalized to a full pupil radius of 1.0. In such a presentation, a perfect system exhibits a straight line parallel to the abscissa. An out of focus condition is represented as a straight inclined line and aberration as various forms of curvature to the line.

3.1.1 Effects of Articulated Secondary

A true Ritchey-Chrétien telescope, correctly manufactured and aligned, is completely free of third order coma. The chief residual design aberrations are astigmatism and field curvature. However, when the secondary mirror is tilted somewhat, to correct for a telescope mispointing of up to 2 arc-sec, this introduces a small amount of axial coma - the effects of which on the fine pointing system performance are worthy of study.

Assume that the fine guidance sensor operates as a four quadrant device, achieving a null condition by balancing the incident energy received by each of the four quadrants. In this manner, the fine guidance head will lock onto the median point of the guide star image; defined as that point through which any straight line will divide the image plane guide star energy into two equal parts. For an image from a perfectly aligned telescope this point corresponds to the position of peak intensity and also to the geometric center of the Airy Disc.

However, for off-axis images when the secondary is tilted, each of these points - the geometric center, position of peak intensity and median point - are separated by small amounts. This separation is of no consequence to the offset guide star tracking concept provided that if the secondary mirror is tilted to compensate for a maximum mispointing, no unacceptable change in separation of these points occurs.

To determine what constitutes an unacceptable change in this separation, the stability of the data star image must be considered. When the secondary mirror is tilted to compensate for 2 arc-sec telescope mispointing, the energy within the Airy disc of the data star image suffers approximately the same redistribution as does the guide star. This might be expected since the

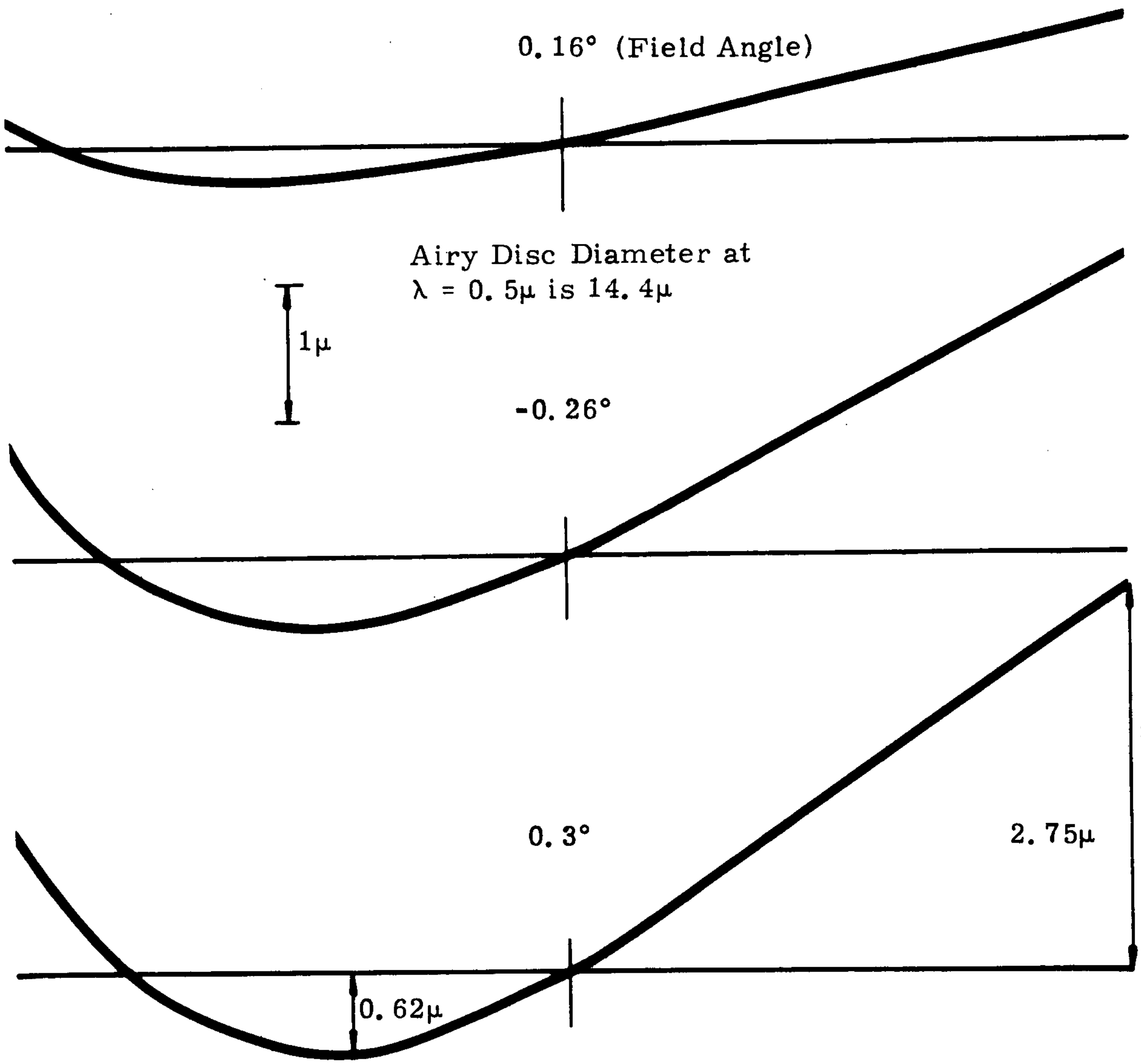

Figure 6. Ritchey-Chretien Telescope, Lateral Aberration Curves

coma introduced by tilting the secondary is field independent. This energy redistribution does in fact give rise to a small shift in the position of the first dark ring on the image plane. This shift must also be taken into account in considering the effects of articulating the secondary.

The position of the guide star image median point was computed for a guide star 18 arc-min off-axis with the secondary mirror in its perfectly aligned condition, and then again with the secondary mirror fully tilted to compensate for 2 arc-sec telescope mispointing. The resulting change in the position of the median point is 0.6μ.

Also, the motion of the data star image was found by computing the displacement necessary to maximize the energy passing through a fixed image plane aperture the size of the Airy pattern first dark ring. This was found to be approximately 0.55μ to 0.58μ in the same direction as the guide star median point shift.

The difference, then, between guide star median point shift and data star image shift is of the order of 0.05μ or less. Compared to a design goal of fine guidance to within 1/10 Airy disc diameter, or 1.5μ, this is insignificant.

Thus, it may be concluded that, using a tracking scheme which follows the guide star image median point, and defining the optimum position of the data star as that which maximizes the energy passing through a fixed aperture the size of the first dark ring, articulating the secondary causes no undesirable effects for up to 2 arc-sec telescope mispointing.

Although it is true that the small amount of coma introduced by tilting the secondary could be removed by a small decentration of the secondary (i.e., by tilting the mirror about some point behind it), the amount of coma introduced is very small, and does not appear to be significantly degrading in performance to warrant the considerable additional mechanical complexity of articulating the secondary about a point other than its center of gravity.

The foregoing argument is equally valid if an image dissector is used as the tracking error detector rather than a four quadrant divider, since most of the proposed image dissector scan patterns rely on a certain symmetry to the guide star image energy distribution.

3.2 8X DATA RELAY

Prior to the detail design of the 8X Data Relay, a preliminary investigation was performed in order to determine the precise form of relay best suited to the system. An on-axis form would have obvious advantages in terms of symmetry, ease of mounting, manufacturing and alignment, but would be appreciably longer than a corresponding off-axis design, due to the constraint that the relay should introduce no additional central obscuration beyond that already present in the Ritchey-Chrétien telescope design.

As a result of this preliminary study (Perkin-Elmer Report No. 11378), it was concluded that an on-axis form was not possible within the constraints of total length limitation and the performance requirements. An off-axis design was therefore pursued in detail (Figure 7).

The detail design of the two element off-axis relay system is summarized in the lens design data sheet, Table 6.

Each mirror is an off-axis section of an oblate spheroid; both mirrors being aligned co-axially. The optical axis of the relay system is parallel to, but displaced 20.7 mm from, the Ritchey-Chrétien optical axis.

The relay design, itself, introduces no obscuration. The central obscuration listed in the design data sheet is that due to the Ritchey-Chrétien telescope. Assembly/alignment tolerances for this relay design are shown in Table 7. This table has been divided into two parts: one providing initial assembly tolerances, allowing focus adjustment, and the other providing a set of stability criteria which must be met in order to preserve optimum performance over a long time interval, without adjustment.

The 12.7 mm object field diameter corresponds to a nominal 3 arc-min telescope data field at the Ritchey-Chrétien f/12 image plane. The relay magnification is 8X, so this object field is presented as a 102 mm diameter image field at f/96 to the data sensor.

The relay system has been designed to accommodate a 3 arc-min field rather than the required 2 arc-min field in order that the same optics may simultaneously relay the guide star images just outside the data field, when used in conjunction with an image mover tracking scheme.

The worst case rms optical path difference at the edge of the 3 arc-min field is less than $\lambda/10$, and the optical performance is significantly better than this over the central 2 arc-min data field.

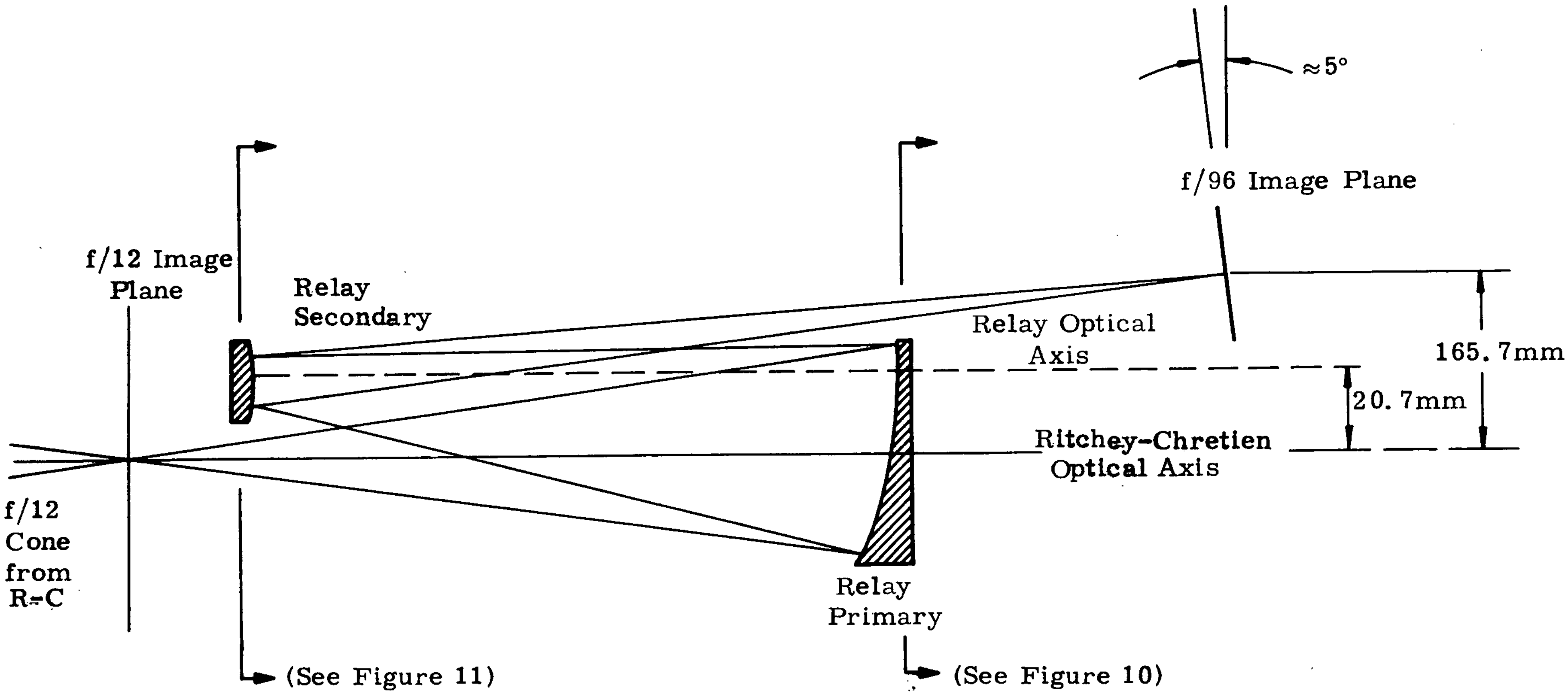

Figure 7. .8X Data Relay - Optical Schematic (not to scale)

TABLE 6. 8X DATA RELAY DESIGN

PERKIN-ELMER
OPTICAL OPERATIONS DIVISION
SOUTH WILTON, CONNECTICUT

LENS DESIGN DATA SHEET

SHEET 1 OF 1

SPO/WO.	DATE	RECOMP.	DESIGN NO.
40649/30,200	3/23/73		

EQUIVALENT FOCAL LENGTH		MAGNIFICATION	
APERTURE RATIO	OBJECT SPACE F/ 12	FIELD AND FORMAT	OBJECT SPACE 12.7 mm off axis 20.7
	IMAGE SPACE F/ 96		IMAGE SPACE 102.0 mm off axis 165.9
DISTANCES	OBJECT TO IMAGE 3011.6	FRONT VERTEX TO BACK VERTEX	1478.3
	FRONT VERTEX TO OBJECT 1404.2	FRONT VERTEX TO ENTRY PUPIL	-5052.2
	BACK VERTEX TO IMAGE 2882.5	BACK VERTEX TO EXIT PUPIL	-1708.1
	FIRST PRINCIPAL POINT -1163.7	SECOND PRINCIPAL POINT	-2147.0
STOP POSITION	-	STOP SIZE (AT MAX. APERT.)	-
TRANSMISSION	-	OBSTRUCTION RATIO	0.3 from Ritchey-Chretien
SPECTRAL RANGE:	MED. WAVELENGTH	MIN. WAVELENGTH	MAX. WAVELENGTH

NO.	FIGURE TOL.	SURFACE NO.	CLEAR APERT.	RADIUS	± TOL.	AXIAL DISTANCE	± TOL.	GLASS TYPE	GLASS CODE	GLASS MELT NO.
1	λ/20	120-70	(1)	-1743.6 (3)	-0 +8	1607.4		Mirror		
2	*	80-50	(2)	-1001.9 (4)	-5 +0	-1478.3		Mirror		
				∞		2882.5		Back focus		

(1) 151.9 diameter (+55.3 to -96.6)

(2) 37.5 diameter (+33.2 to -4.3)

(3) conic constant E = +1.069745 - x = x spherical - 1.64468(10^{-12}) Y^4 (AX_{PP} = 0.143μ)

(4) conic constant E = +4.96659 - x = x spherical - 4.93008 (10^{-10}) Y^4 (AX_{PP} = 0.606μ)

* Figure secondary mirror to obtain system rms OPD of λ/10 or better at edge of 3 arc-min field.

NOT REPRODUCIBLE

TABLE 7. STRUCTURAL AND ALIGNMENT TOLERANCE SUMMARY

Structural Stability Tolerances				Initial Alignment Tolerances		
Tolerance	Resulting rms OPD μ	ΔH' Axis	Deviation	Tolerance	Resulting rms OPD μ	ΔH' Axis
	0.032	0.0	None Nominal Design		0.032	0.0 mm
0.3μ	0.032	5μ	Decenter Primary with respect to secondary	± 0.2 mm	0.051	+ 2.96 mm
±0.04 $\widehat{\mathrm{sec}}$	0.032	5μ	Tilt Primary with respect to secondary	± 1 arc-min	0.058	+ 7.53 mm
±0.01 mm	0.032		Separation between primary/secondary	± 0.05 mm	0.062	

These tolerances assume that the guide star image is not relayed by the data relay mirrors. They will be significantly increased if this is eventually the case: -

The relay also relays guide star image,

±7μ	100μ	Decenter Primary with respect to secondary optical axis
±1 arc-sec	100μ	Tilt primary with respect to secondary optical axis

Field distortion over the 2 arc-min data field corresponds to 0.003 arc-sec in object space and this deteriorates in the region between 2 arc-min and 3 arc-min to approximately 0.015 arc-sec in object space.

Considerable effort has been expended during the course of this design to keep field distortion within acceptable limits. Such distortion has been considered highly undesirable in the 2 arc-min data field especially for viewing extended objects. Such known distortion as would be introduced by the relay system, however, could be removed by electronic data processing of the final image - something that will in all probability be done, anyway. Electronic processing of the final image was not an initial condition of this design effort, however, and so has not been assumed. Obviously, if such processing is adopted, then the relay system could be simplified in form.

The relay system lateral aberration is shown in the lateral aberration curves, Figure 8, and distortion characteristics in Figure 9. The clear apertures required by the folded design are shown in the plane of each of the mirrors in Figures 10 and 11.

3.3 OFFNER-ROSIN PLATE CORRECTORS

Based on Rosin's original proposal[1] of a pair of inclined plane parallel plates for local correction of field astigmatism in a Ritchey-Chrétien telescope, this adaptation - due to Offner - employs four such plates, so designed as to correct for astigmatism and field curvature.

One pair of plates tilts in the tangential direction, the other pair in the radial direction. By proper choice of plate thickness for each pair, a given tilt angle can be made to provide the optical path correction necessary for both astigmation and curvature of the field.

In the case of this design, the relevant plate thicknesses are:

Tangential plates, each 10.663 mm of fused silica N = 1.4585

Radial plates, each 7.440 mm of fused silica N = 1.4585

The angle of inclination of the plates necessary to achieve full correction will vary from close to 0° to approximately 45°, depending on field position, as shown in Figure 12. Once set, this angle must be stable to within ±0.02°, and tilt stability in the direction along the pivot axis must be within ±0.06°.

---

[1] S. Rosin and M. Armor, Appl. Optics 11, 7, (1972)

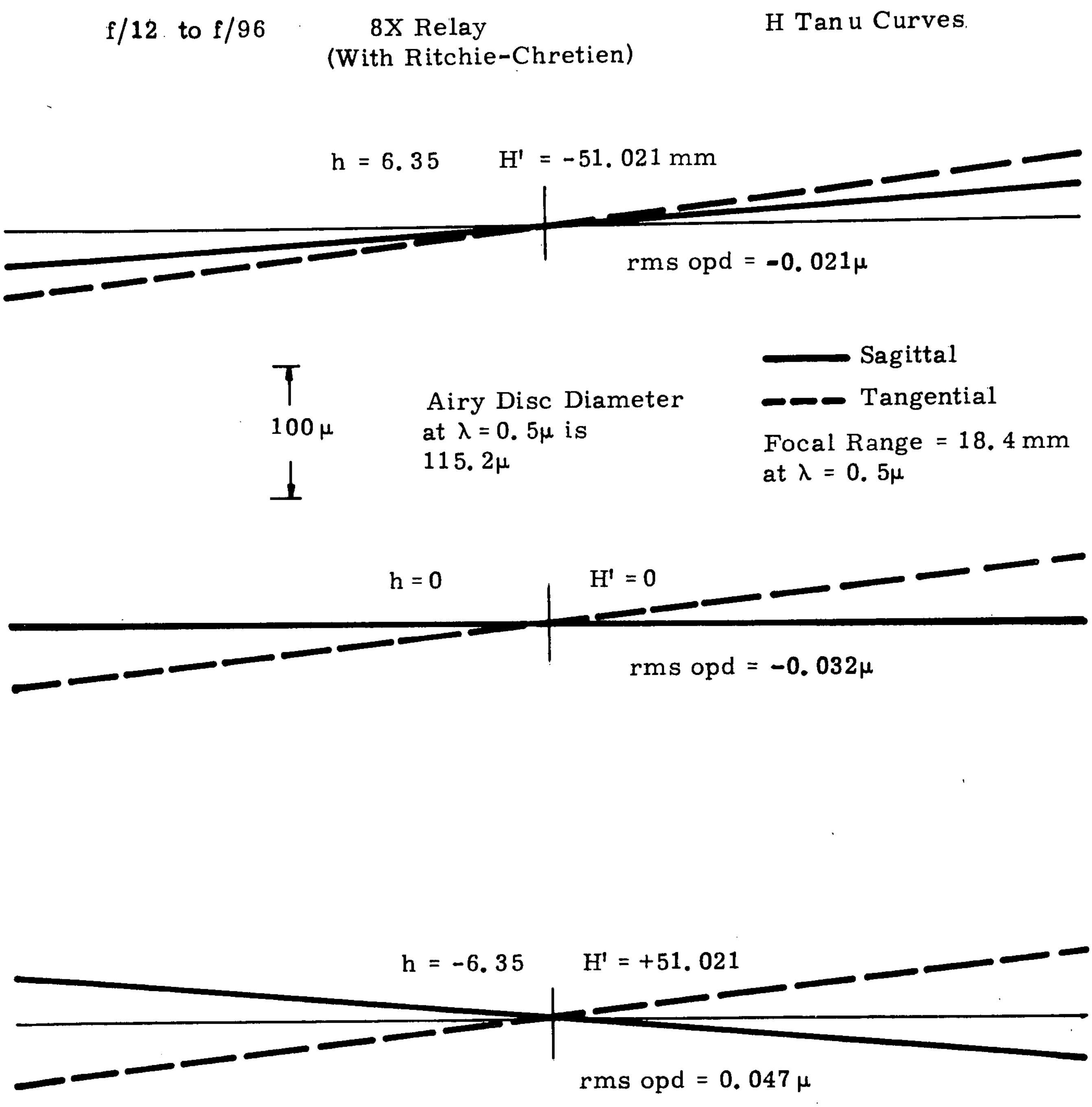

Figure 8. 8X Relay Lateral Aberration

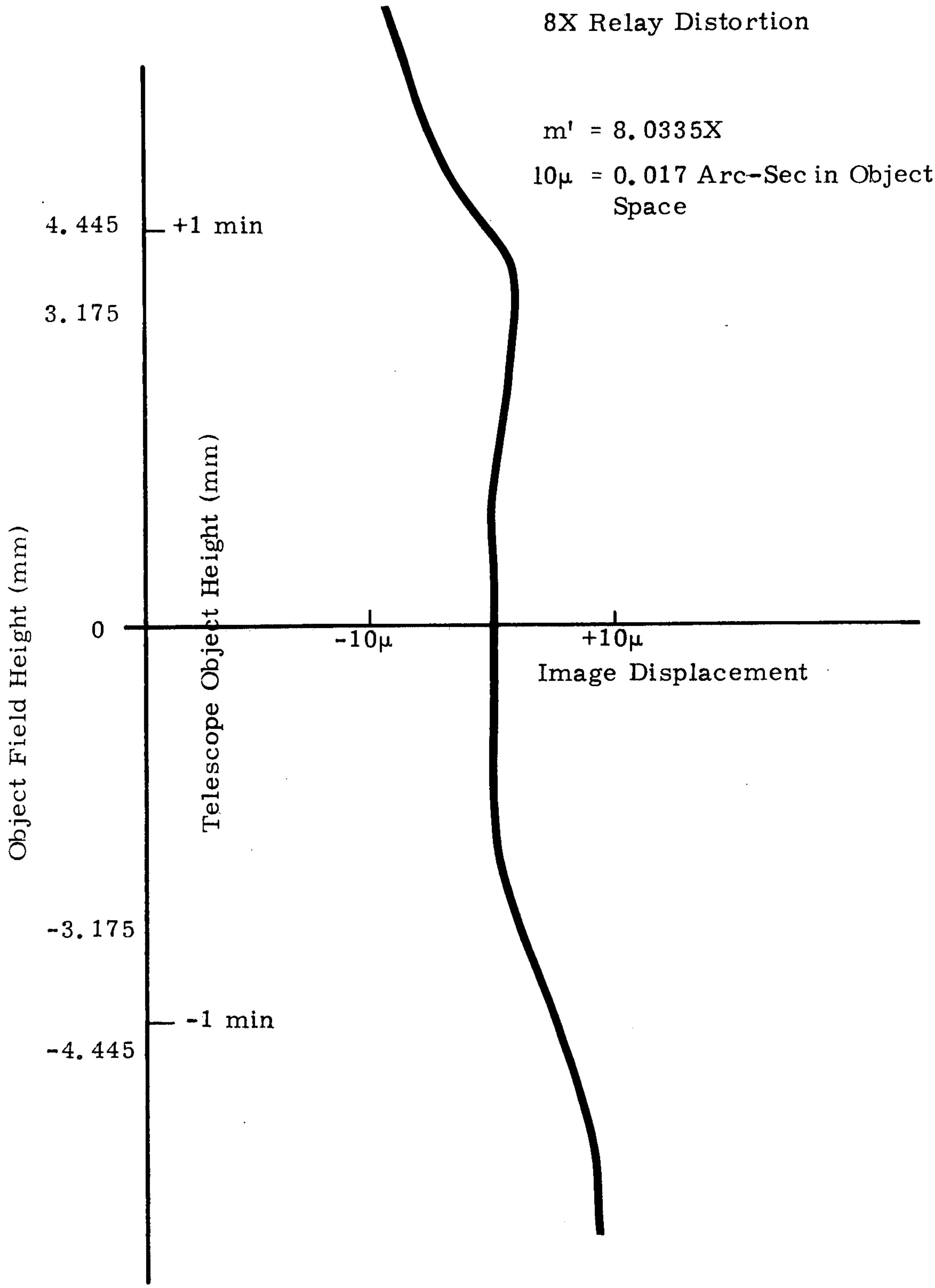

Figure 9. 8X Relay Distortion

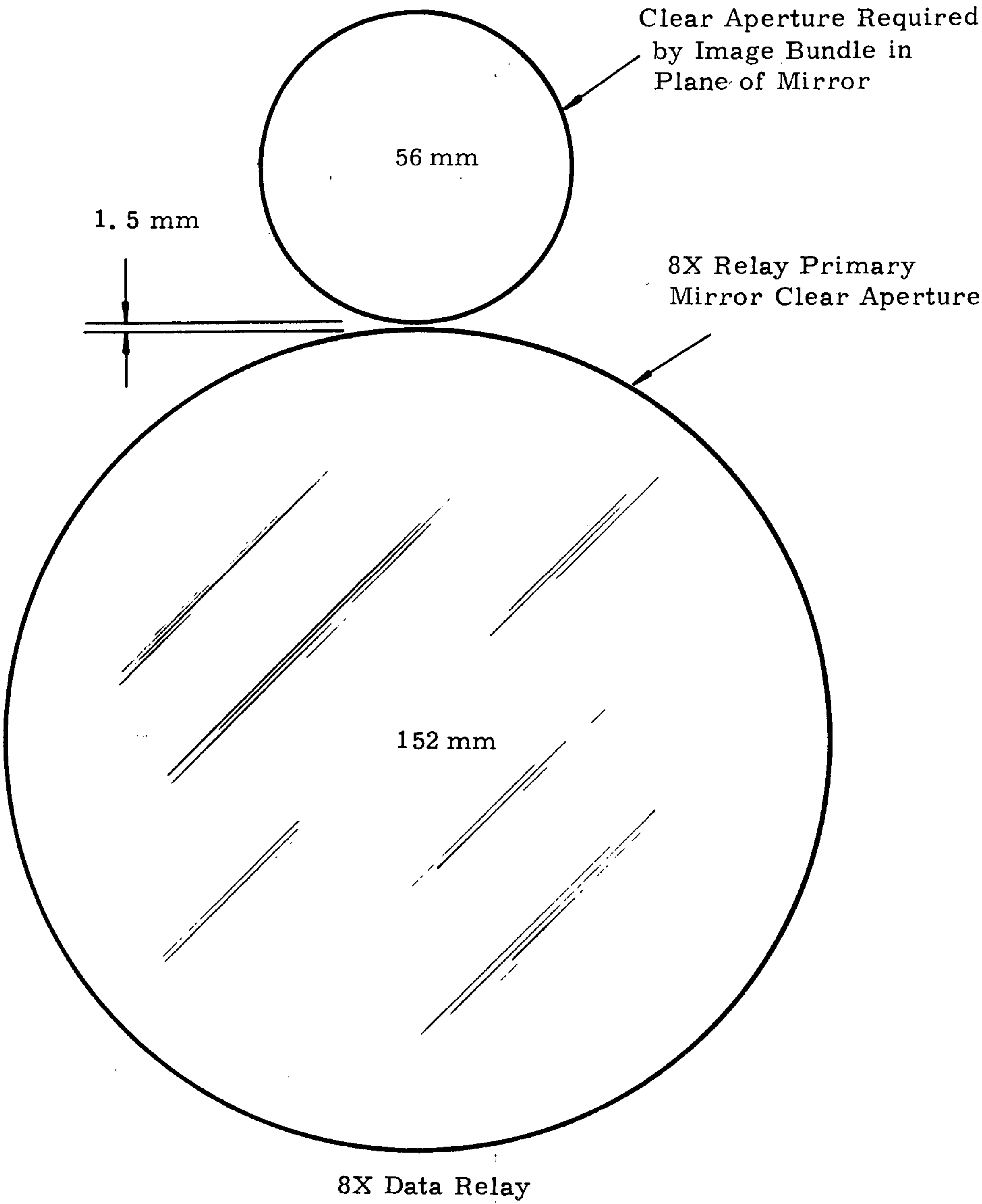

Figure 10. Relay/Primary Clear Aperture

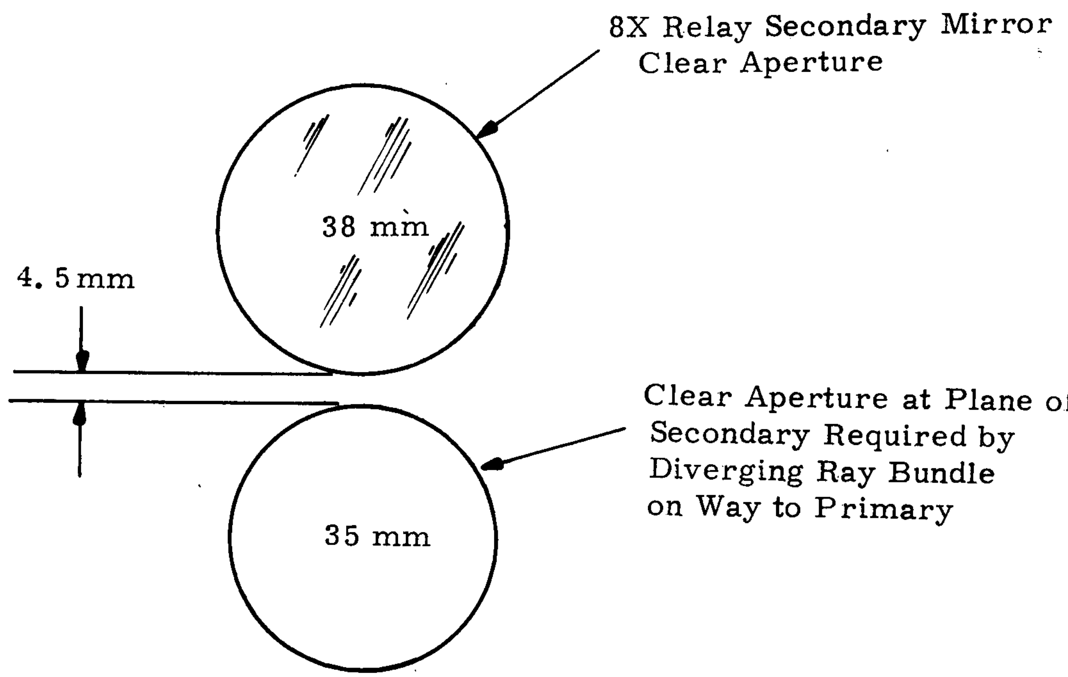

Figure 11. Relay/Secondary Clear Aperture

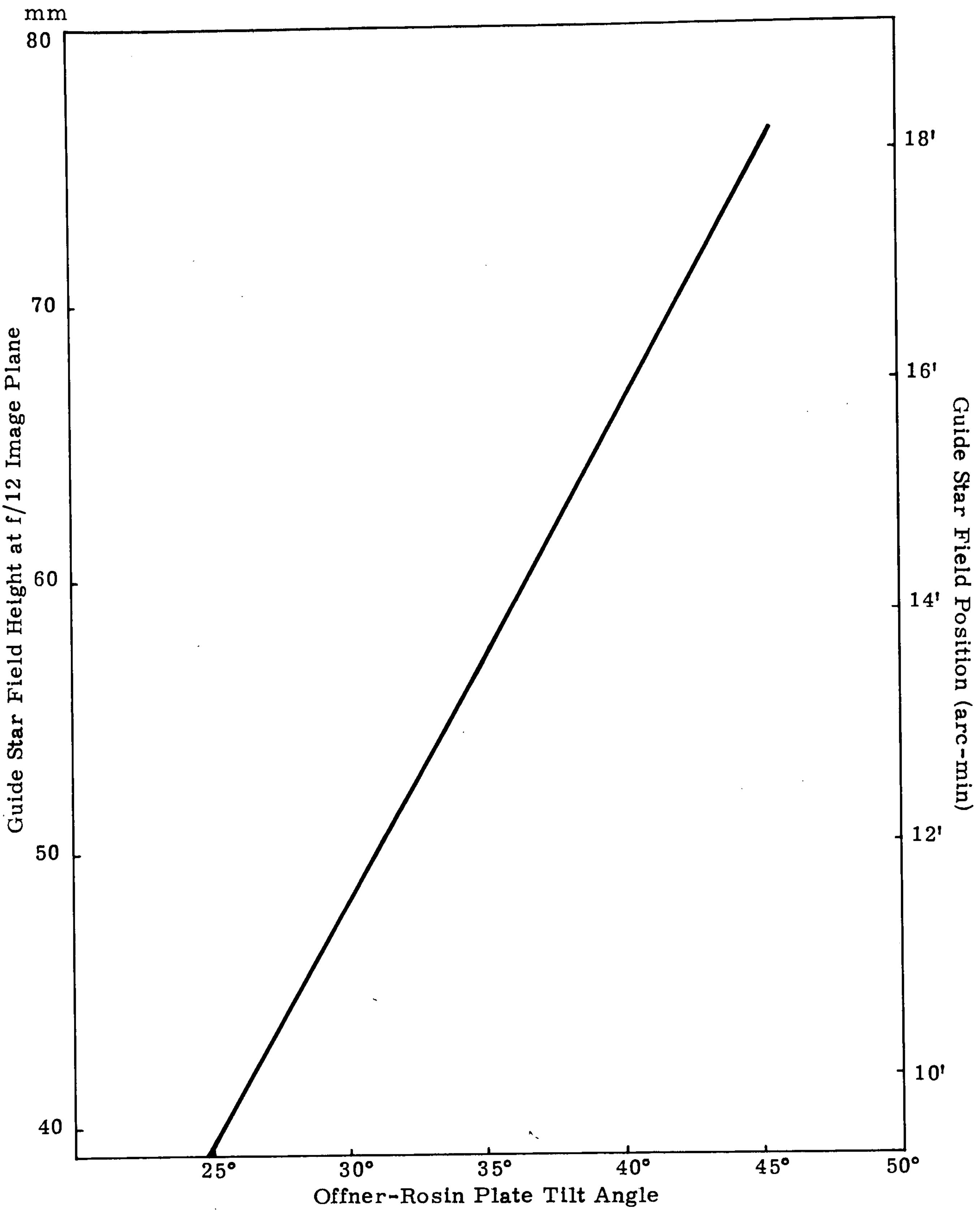

Figure 12. Offner-Rosin Plate Required Tilt Angle

Since the Offner-Rosin plate assembly requires a mechanical rotation input which is a function of field position, it lends itself to incorporation into the front end of an image mover assembly (paragraph 3.4). That assembly also requires a shaft rotation which is a function of field position. Preliminary layouts indicate the two systems to be very compatible. The Offner-Rosin plates themselves used in this manner, are quite small, requiring clear apertures of only about 10 mm diameter. To account for obliquity factors, therefore, the largest plate should be approximately 30 mm in diameter. The OPD of each plate, in transmission, should be $\lambda/10$ rms and wedge angle within the plate should not exceed 1 arc-min.

3.4 IMAGE MOVER

The fundamental element of the tracking scheme is the image mover, which is designed to intercept the converging f/12 bundle of a guide star image and relay it, at unity magnification, to a fixed output point just inside the field of view of the data relay (but outside the data field).

In this manner, the guide star is relayed to the f/96 plane by the same optical elements as the data star, and tracking is achieved through the whole system. The only elements not common to data and guide star channels are the elements of the corrector plates and image mover elements themselves. Since these are small elements, in a compact package, their stability is more easily controlled.

The image mover is comprised of a negative lens, articulated in such a manner as to be able to locate a guide star within the guidance field, fold mirrors or prisms, and a refocusing lens at the fixed output axis. The negative lens collimates the f/12 bundle. This collimated bundle is then folded into the axis of the positive element, positioned so that the output f/12 bundle falls just within the data relay field of view (Figure 13). To account for the field angle of the chief ray in the f/12 bundle the negative element will, in general, work slightly off-axis. However, by proper choice of focal lengths, the negative lens axis has been made always to pass through the nominal guide star image position in the telescope f/12 image plane. This is shown in an exaggerated sense in Figure 14.

The detailed design of the image mover lenses is summarized in the lens design data sheet, Table 8.

Since the image mover is an optical system of unity magnification, the output cone chief ray is parallel to the input cone chief ray. That is, the field angle is unchanged by the image mover. Thus, although the guide star image is translated by the image mover system to a point just within the field of the data relay, the field angle of the emergent guide star ray bundle is

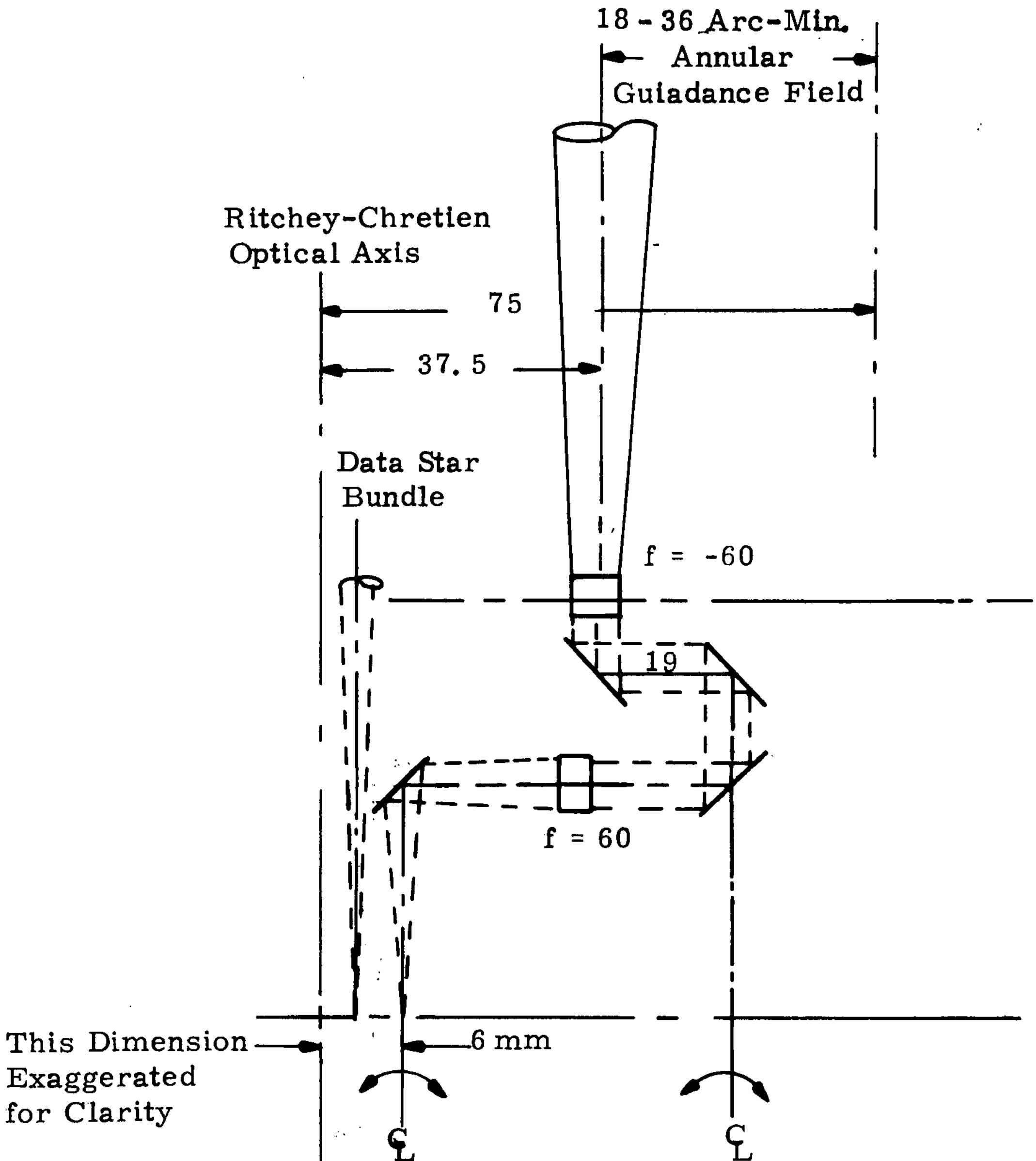

Figure 13. Image Mover Optical Layout (Full Scale)

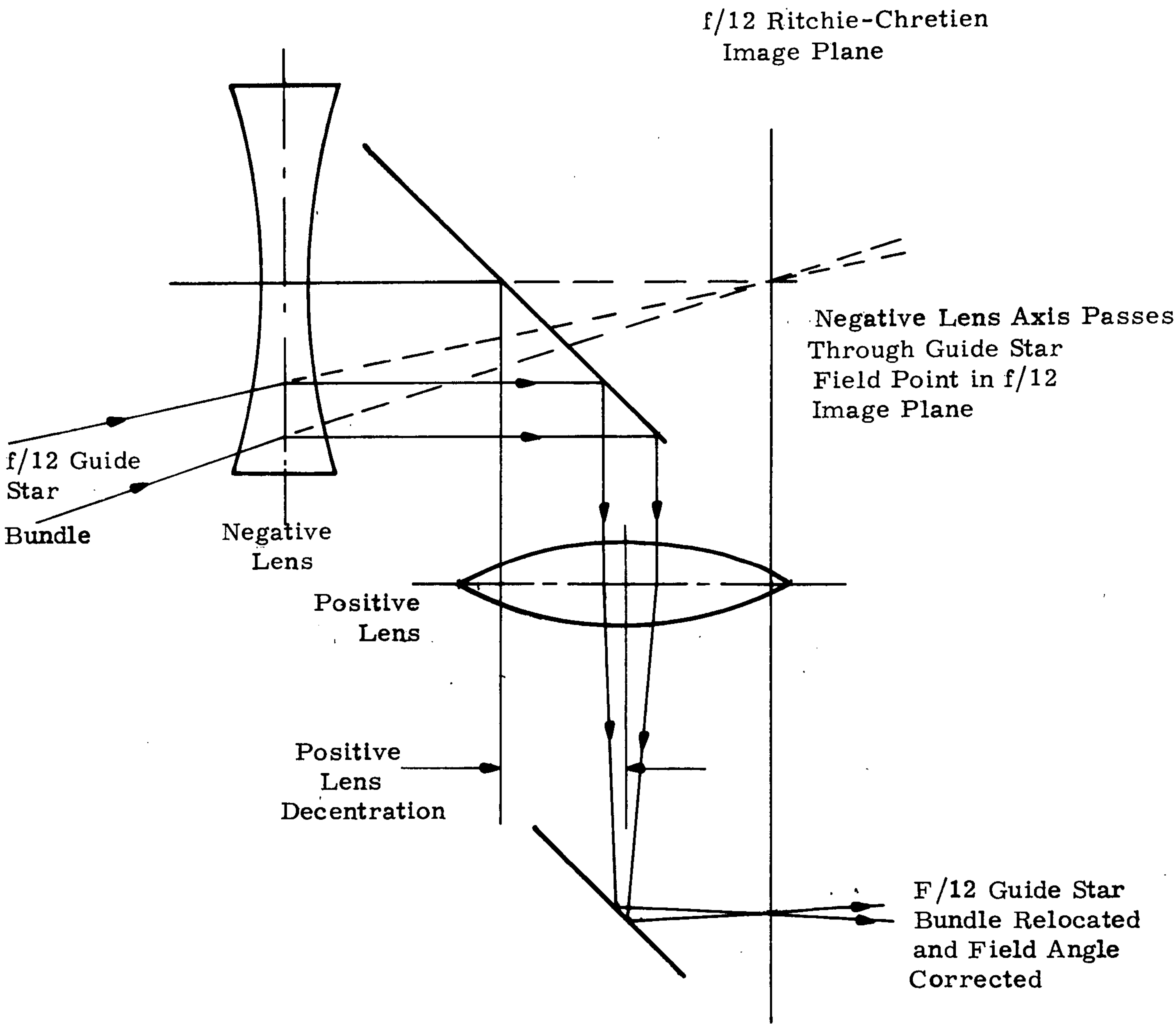

Figure 14. Image Mover Lens Decentrations

TABLE 8. IMAGE MOVER DESIGN

PERKIN-ELMER
OPTICAL OPERATIONS DIVISION
SOUTH WILTON, CONNECTICUT

LENS DESIGN DATA SHEET

SHEET 1 OF 1

SPO/WO.	DATE	RECOMP.	DESIGN NO.
40649/30	3/23/72		

EQUIVALENT FOCAL LENGTH 46.57		MAGNIFICATION	
APERTURE RATIO	OBJECT SPACE F/ 12	FIELD AND FORMAT	OBJECT SPACE 0.5 arc-min full field
	IMAGE SPACE F/ 12		IMAGE SPACE
DISTANCES	OBJECT TO IMAGE 80.5	FRONT VERTEX TO BACK VERTEX	86.2
	FRONT VERTEX TO IMAGE 143.0	FRONT VERTEX TO ENTRY PUPIL	-3452.6
	BACK VERTEX TO IMAGE 56.8	BACK VERTEX TO EXIT PUPIL	104.2
	FIRST PRINCIPAL POINT 62.7	SECOND PRINCIPAL POINT	57.0
STOP POSITION --		STOP SIZE (AT MAX. APERT.)	--
TRANSMISSION --		OBSTRUCTION RATIO	--
SPECTRAL RANGE: 5876 MED. WAVELENGTH	4861 MIN. WAVELENGTH	6563 MAX. WAVELENGTH	

NO.	FIGURE TOL.	SURFACE NO.	CLEAR APERT.	RADIUS	± TOL.	AXIAL DISTANCE	± TOL.	GLASS TYPE	GLASS CODE	GLASS MELT NO.
1	λ/8	60-40	6.6	-172.55	2λ	2.0	0.1	F4	NH1	
2	λ/2	60-40	6.6	-25.349	2λ	3.0	0.1	BK7	NH1	
3	λ/8	60-40	6.6	30.137	2λ	76.2	0.2	AIR		
4	λ/8	60-40	6.4	29-997	2λ	3.0	0.1	BK7	NH1	
5	λ/2	60-40	6.4	-23.61	2λ	2.0	0.1	F4	NH1	
6	λ/8	60-40	6.4	-163.492	2λ	56.8				

REMARKS:
All lenses: wedge tolerance - 5μ

exactly the same as for the undisturbed guide star image - which will in general be somewhere between 9 $\widehat{\min}$ and 18 $\widehat{\min}$. This means that the relay mirrors will have to be of sufficient aperture to accommodate this field angle. What would, for data purposes only, be an f/12 relay will in fact have to be an f/10 relay if it is also to carry a guide star image from a simple image mover.

To change the present relay design from f/12 to f/10, would mean that the relay mirrors would then work further off-axis, increasing the resultant distortion. To reduce the distortion to acceptable limits would require a longer relay, and/or more aspheric surfaces.

Such a complication to the present relay system design (paragraph 3.2) has been deemed unacceptable, and an alternate solution is here proposed.

The field angle of the emergent bundle may be controlled, without unacceptable image degradation, by decentering the final positive lens element to the image mover. The actual decentration amount is dependent upon the guide star field position, but for 18 arc-min would be approximately 1.25 mm (Figure 14). Such a programmed decentration could be built into the image mover mechanics with little additional complication. The only real problem with such an approach is that it introduces one more moving component, which must be locked with high stability for the duration of an exposure.

As mentioned in paragraph 3.2, if electronic data processing of the final image is adopted, the relay lens can be designed with no great difficulty to accommodate the guide star field angle without the added complexity of decentering the image mover positive lens.

The prime causes of instability during an exposure are expected to be lens tilt or lens decentration due to a changing thermal environment. Such tilts must be controlled to be within ±0.5 arc-secs for each lens, and decentrations to within ±0.5 μ.

3.5 F/12 GUIDANCE

This is an alternate to the image mover tracking concept involving separation of the data and guide star optical paths. The corrected guide star image is received at the flattened f/12 image plane and magnified by an 8X refractive relay and presented to the detector device; either four quadrant divider or image dissector tube. Relative motion between the f/12 image plane, where tracking is performed, and the f/96 plane, where data is gathered, is monitored by a separate internal metering system.

3.5.1 Relay Lens Design

The detail design parameters for this lens, a four element group, are presented in lens design data sheet, Table 9. The magnification is 8X, so that tracking is performed on an f/96 image, but the lens itself is compact so that the physical location of the tracking detector is close to the f/12 prime image plane. This catalog design has been color corrected for the spectral region 5,000Å to 6,000Å. Correction could be modified to other spectral regions, if necessary, depending upon the spectral sensitivity of the photocathode material eventually used. The lens group layout is shown, to scale, in Figure 15.

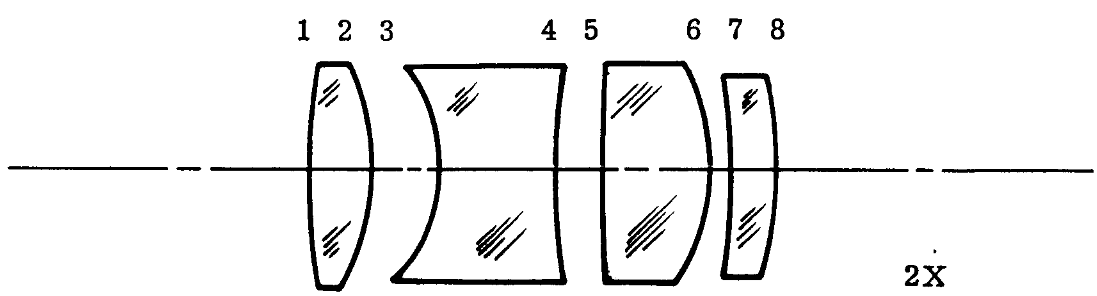

Figure 15.. F/12 Guidance Relay Lens

TABLE 9. REFRACTIVE RELAY DESIGN

PERKIN-ELMER
OPTICAL OPERATIONS DIVISION
SOUTH WILTON, CONNECTICUT

LENS DESIGN DATA SHEET

SHEET 1 OF 1

SPO/WO.	DATE	RECOMP.	DESIGN NO.
40649/30	3/23/73		

EQUIVALENT FOCAL LENGTH

MAGNIFICATION

APERTURE RATIO	OBJECT SPACE F/ 12	FIELD AND FORMAT	OBJECT SPACE	
	IMAGE SPACE F/ 96		IMAGE SPACE	
DISTANCES	OBJECT TO IMAGE 337.7580	FRONT VERTIX TO BACK VERTEX 29.46		
	FRONT VERTEX TO IMAGE 322.694810	FRONT VERTEX TO ENTRY PUPIL 0.0		
	BACK VERTEX TO IMAGE 293.234768	BACK VERTEX TO EXIT PUPIL -82.991465		
	FIRST PRINCIPAL POINT 22.992198	SECOND PRINCIPAL POINT -11.208232		
STOP POSITION 0.0 from surface #1		STOP SIZE (AT MAX. APERT.) 1.255265		
TRANSMISSION --		OBSTRUCTION RATIO 0.3 from Ritchey-Chertien		
SPECTRAL RANGE: 5,500 MED. WAVELENGTH		5,000 MIN. WAVELENGTH	6,000 MAX. WAVELENGTH	

NO.	FIGURE TOL.	SURFACE NO.	CLEAR APERT.	RADIUS	± TOL.	AXIAL DISTANCE	± TOL.	GLASS TYPE	GLASS CODE	MELT NO.
			0.50	∞		15.0632		AIR		
1	1/4λ	80-50	1.26	51.0874		3.9		LAF22		
2	1/4λ	80-50	1.70	-17.1057		4.93		AIR		
3	1/4λ	80-50	2.33	-9.4325		7.00		SF11		
4	1/4λ	80-50	3.62	37.8913		2.35		AIR		
5	1/4λ	80-50	4.57	101.0730		7.00		BK50		
6	1/4λ	80-50	6.24	-14.9904		0.93		AIR		
7	1/4λ	80-50	6.43	-114.9479		3.35		SK16		
8	1/4λ	80-50	6.82	-26.3903		293.2348		AIR		
9	--		17.28	∞		--		--		

3.5.2 Internal Metering System

A simple and reliable metering concept employs a small light emitting diode, a fast relay lens and a detector (in the form of an image dissector or four quadrant phototube). The single element relay is used to produce a circular far field pattern at the detector head. Its design is very straightforward since it is required to operate monochromatically. A lens of 15 mm focal length and f/2 will be adequate.

3.6 WINDOW

If a window is used at the entrance to the telescope system, its optical properties are of great significance since all other optical elements follow it and operate on the incoming wavefront as aberrated by the window.

Any tolerance on wavefront deviation ascribed to the window, then places more stringent specifications on all succeeding elements by using up part of the overall allowable error budget. For purposes of this study, the window has been allowed 1/50 wave rms OPD and up to 1/4 wave spherical power. (Power can be removed by a small focus adjustment.) Its thickness must be such as to maintain these tolerances in the presence of whatever operational pressure difference might be applied. The diameter of the window should be such that a minimum clear aperture of 1.25 m is available.

3.7 BAFFLES

Experience gained with other comparable optical systems has demonstrated the very significant gains in performance possible from extensive stray light suppression schemes. The diversity of instrumentation and astronomical application planned for LST will benefit greatly from the implementation of such a scheme and from its development and proving on the LST engineering technology model.

However, a detailed baffle design cannot be undertaken until all telescope instrumentation, including alignment, focus and figure sensors, have been designed and their integration into the LST defined.

3.8 COARSE ACQUISITION CAMERA

The coarse acquisition camera will be used as the coarse field aiming device, just as a guide telescope is used to aim a ground based telescope. It is required to view a 2° diameter field, and to be boresighted to the line of sight of the main telescope.

The image field of the coarse acquisition camera is to be received by an image orthicon or similar TV system. In the absence of more detailed information on the proposed TV system, the lens has been designed as a 2° field, f/4, diffraction limited Catadioptric - color corrected over the broad spectral region from 4047Å to 7000Å.

The design details of the lens are shown in lens design data sheet, Table 10, and a schematic layout of the assembly in Figure 16. This particular catadioptric form of design was chosen since it is easiest to compensate chromatically over a wide region, and results in a rugged, compact design which is both simple and economic to manufacture, since all the optical surfaces involved are purely spherical.

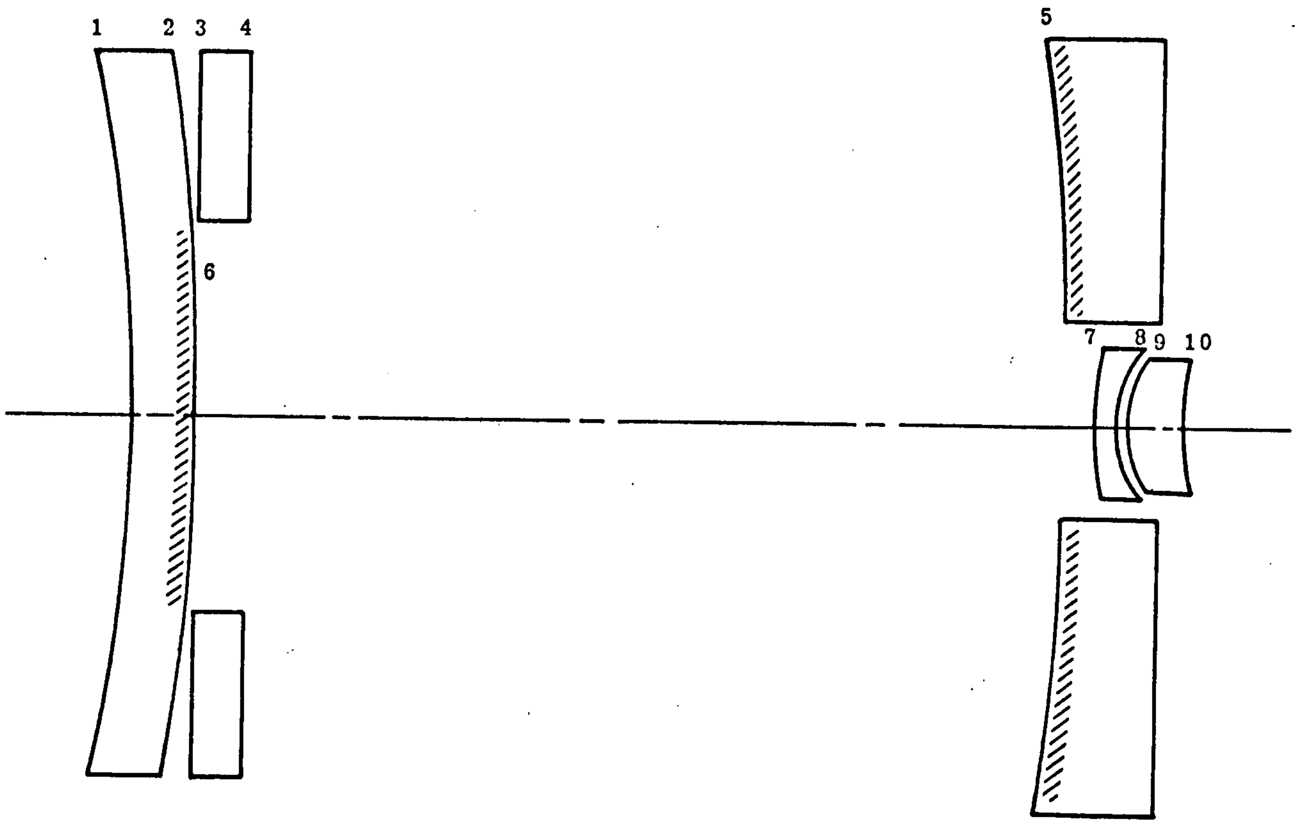

Figure 16. Coarse Acquisition Camera Lens - Optical Layout

TABLE 10. COURSE ACQUISITION CAMERA DESIGN

PERKIN-ELMER
OPTICAL OPERATIONS DIVISION
SOUTH WILTON, CONNECTICUT

LENS DESIGN DATA SHEET

SHEET 1 OF 1

S.O./W.O.	DATE	RECOMP.	DESIGN NO.
40649/30	3/23/73		

EQUIVALENT FOCAL LENGTH		MAGNIFICATION	
APERTURE RATIO	OBJECT SPACE F/ ∞	FIELD AND FORMAT	OBJECT SPACE 1° semi-angular field
	IMAGE SPACE F/ 4		IMAGE SPACE 15.8 mm diameter
DISTANCES	OBJECT TO IMAGE ∞	FRONT VERTIX TO BACK VERTEX	
	FRONT VERTEX TO IMAGE	FRONT VERTEX TO ENTRY PUPIL 0.0	
	BACK VERTEX TO IMAGE 30.04	BACK VERTEX TO EXIT PUPIL	
	FIRST PRINCIPAL POINT	SECOND PRINCIPAL POINT	
STOP POSITION 0.0 from surface #1		STOP SIZE (AT MAX. APERT.)	
TRANSMISSION		OBSTRUCTION RATIO 0.46	
SPECTRAL RANGE: 5,461 MED. WAVELENGTH	4,047 MIN. WAVELENGTH	7,682 MAX. WAVELENGTH	

NO.	FIGURE TOL.	SURFACE NO.	CLEAR APERT.	RADIUS	± TOL.	AXIAL DISTANCE	± TOL.	GLASS TYPE	GLASS CODE	GLASS MELT NO.
1	1/2λ		125.3	-266.160	1	10,15	±0.01	BK-7		
2	1/2λ		127.1	-399.289		0.0	±0.01	AIR		
3	1/2λ		127.9	844.465		9.13	±0.01	BK-7		
4	1/2λ		128.1	∞		143.86	±0.01	AIR		
5	1/4λ		133.3	-503.438		-153.00	±0.01	AIR		
6	1/4λ		57.8	-399.289		156.41	±0.01	AIR		
7	1/2λ		25.3	54.713		4.06	±0.01	BK-7		
8	1/2λ		23.3	17.733		0.36	±0.01	AIR		
9	1/2λ		23.4	18.038		8.73	±0.01	BK-7		
10	1/2λ		21.7	40.518		30.04	±0.01	AIR		
11		image plane	15.8	∞						

NOT REPRODUCIBLE

SECTION IV

SYSTEM TOLERANCE ANALYSIS

The LST will provide a wide range of instrumentation capability over an extended lifetime and will require flexibility for instrument checkout, repair and replacement. The concept of modular design should greatly facilitate attainment of these objectives. To the extent possible, each subsystem should be self-contained and qualificable prior to its assembly into the LST system.

The LST Engineering Scale Model is specified to follow the modular concept. As shown in Figure 17, the system is composed of four basic sections (or modules):

1. The Ritchey-Chrétien telescope objective (including the aperture window)

2. The eight power reflective data relay

3. Fine Guidance Optical System

4. Coarse Acquisition System

In analyzing the system tolerances for inter-modular alignment errors, all other modules are referenced to the Ritchey-Chrétien optical axis for tilt and decenter errors and to the Ritchey-Chrétien primary mirror vertex for axial position tolerances. The design specification requires that the data wavefront at f/96 have a wavefront error no greater than $\lambda/10$ rms. The basic optical data elements, the primary, secondary mirror and eight power relay have been designed and toleranced such that the system, when perfectly aligned, will provide an OPD at f/96 not to exceed 0.032λ rms. It will be shown that system alignment and structural stability tolerances (between modules) will be much influenced by the design of the fine guidance system.

The optical element fabrication tolerances and the intra-modular assembly tolerances for both the R/C telescope and the eight power relay are given in Tables 5 and 6. Each is separately assembled, aligned and tested.

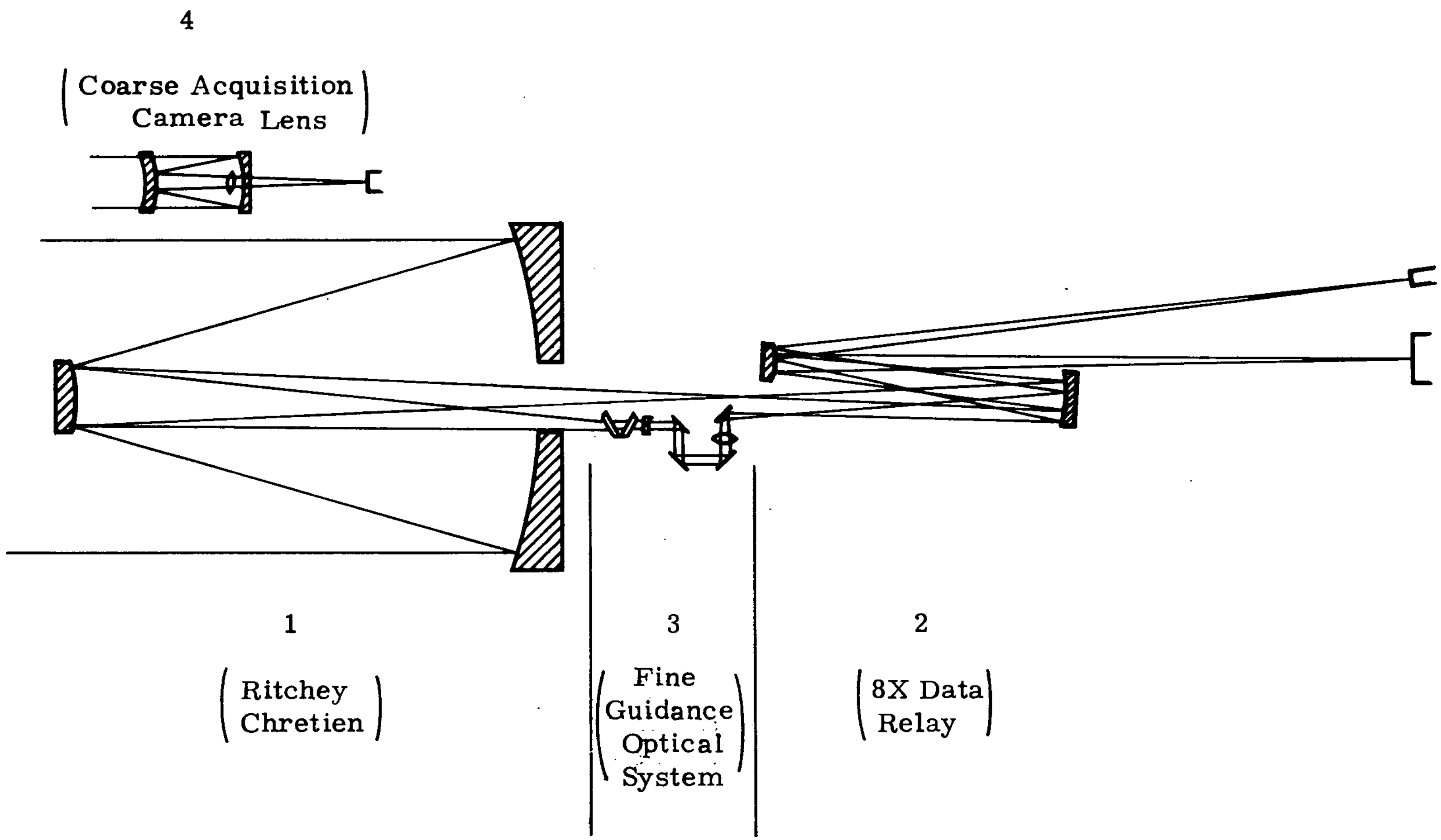

Figure 17. System Module Identification

The key module interface is the positioning of the relay relative to R/C and for this purpose the point of reference on the relay assembly has been defined to be the relay secondary mirror vertex. Although great convenience is derived from thinking of the relay as a separate module, the system tolerance analysis must consider the basic philosophy of LST operation and in this sense the relay tolerances become heavily dependent upon the precise form of the fine guidance system.

Due to its high magnification, the relay assembly must be held very accurately centered and aligned in order that it shall not introduce instabilities in the data star image position over an exposure period. However, if the guide star is also relayed by the same optical elements as the data star, then the fine guidance system will be able to track through the whole telescope optical system and thereby remove small, low frequency disturbances in the relay assembly or instrument support structure. The relay module stability tolerances then become less stringent.

Table 11 defines the tolerances on (1) centering of the relay assembly with respect to the R/C axis and (2) tilt of the relay assembly axis with respect to the Ritchey-Chrétien optical axis. Tolerances are given, for both fine guidance concepts, for initial alignment of the telescope system and for allowable stability shifts before performance degradation is introduced.

In this study, two particular kinds of performance degradation were considered, and the tolerance assigned on the basis of the more sensitive of these. First was wavefront error, at the data image plane, and second was displacement of the data star image at the f/96 image plane, or image motion. In all cases, the more limiting sensitive performance criterion was image motion. When stability tolerances are assigned on the basis of controlling image motion to acceptable levels, there is no measurable change in wavefront error from the nominal design amount of 0.032μ. It is clear that structural stability requirements are much affected by the guidance concept.

4.1 IMAGE MOVER - ROSIN CORRECTOR ASSEMBLY

This movable optical assembly serves to relay (at unity magnification) the guide star to a fixed point at the edge of the data field. It is the single element which is not common to both data and guidance optical paths. Positioning of the image mover assembly relative to the Ritchey-Chrétien is dependent on the accuracy to which a coordinate system needs to be referenced for purposes of locating a guide star by remote control. Thereafter, stability is the prime and critical requirement. The assembly should be stable such that the output converging bundle does not translate more than $\pm 0.5\mu$ or tilt more than approximately ± 0.1 min. during the period of an exposure (this could be up to 10 hours in LST).

TABLE 11. RELAY SYSTEM TOLERANCES

GUIDE STAR NOT RELAYED BY DATA RELAY						
Structural Stability				Initial Alignment Tolerance		
Tolerance	Resulting rms OPD μ	ΔH' Axis	Deviation	Tolerance	Resulting rms OPD μ	ΔH' Axis
	0.032	0.0	None Nominal Design		0.032	0.0
0.6μ	0.032	±5μ	Decenter relay WRT R/C axis	±0.1 mm	0.040	±0.8 mm
0.06 arc-sec	0.032	±5μ	Tilt relay about its secondary mirror vertex	±30 arc-sec	0.040	±0.7 mm
GUIDE STAR IS RELAYED BY DATA RELAY						
±12μ	0.032	100μ	Decenter relay WRT R/C axis	±0.1 mm	0.040	±0.8 mm
±15 arc-sec	0.032	100μ	Tilt relay about its secondary mirror vertex	±30 arc-sec	0.040	±0.7 mm

4.2 ROSIN CORRECTOR - RELAY AT F/12 ASSEMBLY

The Rosin corrector-relay assembly for guidance in the f/12 focal plane is integral with the guidance detector. Similar to the image mover assembly above, its positional accuracy is dependent on the precision of the coordinate system used to locate the selected guide star. Thereafter, the stability of the assembly is critical and should be stable to better than 0.1 Airy disc diameter. Thus, the tolerance in the f/12 plane for translation will be $\pm 0.5\mu$ (1/30 Airy disc) and tilt shall not exceed $\pm 0.1\ \widehat{\text{min}}$.

4.3 F/12 TO F/96 METERING LINK

The components of the metering system (LED, relay and detector) used to monitor relative motion between f/12 and f/96 planes are small, compact, and should be monitored so as to be mechanically integral with the relevant focal plane structures. Displacements due to thermal growth, etc., in use should be controlled so that the minimum anticipated differential displacements is less than $\pm 0.1\mu$.

4.4 COARSE ACQUISITION CAMERA

This camera must be mounted and boresighted to the main telescope line of sight to within $\pm 1\ \widehat{\text{min}}$, and should be designed to remain stable to within $\pm 1\ \widehat{\text{sec}}$. These numbers are somewhat arbitrary in nature since they depend to a large extent on the exact mode of operational use of the camera display. However, in the absence of better definition, this preliminary data will serve as a conservative estimate.

APPENDIX A

PRIMARY MIRROR SAG TABLES

PERKIN-ELMER

ASPHERIC SAG TABLE

LST RAUL 09.48.43 03/19/73

A=-1.731380D-02 B= 0.0 C= 0.0 D= 0.0 E= 0.0

CURV. -1.89394110-04 CURV. SUBTRACTED -1.8873229D-04 SCALING FAC. 1.000

RADIUS(MM) -0.5279995D 04 SUBTRACTED RADIUS(MM) -0.5298510D 04

SURFACE NO. 1

SCALED ASPHERIC COEFFICIENTS
A=-1.731380D-02 B= 0.0 C= 0.0 D= 0.0 E= 0.0

H(MM)	SAG(MICRONS)	SUB SAG (MICRONS) relative to nearest sphere.
0.0	0.0	0.0
5.00	-2.37	-0.008
10.00	-9.47	-0.033
15.00	-21.31	-0.074
20.00	-37.88	-0.132
25.00	-59.19	-0.206
30.00	-85.23	-0.297
35.00	-116.00	-0.404
40.00	-151.52	-0.527
45.00	-191.76	-0.667
50.00	-236.74	-0.822
55.00	-286.46	-0.993
60.00	-340.91	-1.180
65.00	-400.09	-1.383
70.00	-464.02	-1.601
75.00	-532.67	-1.834
80.00	-606.06	-2.083
85.00	-684.19	-2.346
90.00	-767.05	-2.624
95.00	-854.64	-2.917
100.00	-946.97	-3.224
105.00	-1044.03	-3.544
110.00	-1145.83	-3.879
115.00	-1252.37	-4.227
120.00	-1363.63	-4.588
125.00	-1479.64	-4.962
130.00	-1600.38	-5.348
135.00	-1725.85	-5.747
140.00	-1856.06	-6.157
145.00	-1991.00	-6.579
150.00	-2130.68	-7.012
155.00	-2275.09	-7.456
160.00	-2424.23	-7.911
165.00	-2578.12	-8.375

170.00	-2736.73	-8.849
175.00	-2900.08	-9.332
180.00	-3068.17	-9.823
185.00	-3240.99	-10.323
190.00	-3418.54	-10.831
195.00	-3600.83	-11.346
200.00	-3787.86	-11.867
205.00	-3979.62	-12.395
210.00	-4176.11	-12.929
215.00	-4377.34	-13.468
220.00	-4583.30	-14.011
225.00	-4794.00	-14.559
230.00	-5009.43	-15.110
235.00	-5229.60	-15.664
240.00	-5454.50	-16.221
245.00	-5684.14	-16.779
250.00	-5918.51	-17.338
255.00	-6157.61	-17.898
260.00	-6401.45	-18.458
265.00	-6650.03	-19.016
270.00	-6903.34	-19.574
275.00	-7161.38	-20.129
280.00	-7424.16	-20.681
285.00	-7691.67	-21.229
290.00	-7963.92	-21.773
295.00	-8240.90	-22.312
300.00	-8522.62	-22.845
305.00	-8809.07	-23.372
310.00	-9100.25	-23.891
315.00	-9396.17	-24.402
320.00	-9696.82	-24.903
325.00	-10002.21	-25.395
330.00	-10312.33	-25.877
335.00	-10627.19	-26.347
340.00	-10946.78	-26.804
345.00	-11271.11	-27.248
350.00	-11600.17	-27.678
355.00	-11933.96	-28.093
360.00	-12272.49	-28.492
365.00	-12615.75	-28.874
370.00	-12963.75	-29.238
375.00	-13316.48	-29.584
380.00	-13673.95	-29.910
385.00	-14036.15	-30.215
390.00	-14403.08	-30.498
395.00	-14774.75	-30.759

PERKIN-ELMER

400.00	-15151.15	-30.995
405.00	-15532.29	-31.207
410.00	-15918.16	-31.394
415.00	-16308.76	-31.553
420.00	-16704.10	-31.684
425.00	-17104.18	-31.786
430.00	-17508.98	-31.859
435.00	-17918.52	-31.899
440.00	-18332.80	-31.908
445.00	-18751.81	-31.883
450.00	-19175.55	-31.823
455.00	-19604.03	-31.727
460.00	-20037.24	-31.595
465.00	-20475.18	-31.424
470.00	-20917.86	-31.213
475.00	-21365.27	-30.962
480.00	-21817.42	-30.669
485.00	-22274.30	-30.333
490.00	-22735.92	-29.953
495.00	-23202.26	-29.526
500.00	-23673.35	-29.053
505.00	-24149.16	-28.532
510.00	-24629.71	-27.960
515.00	-25114.99	-27.338
520.00	-25605.01	-26.664
525.00	-26099.76	-25.936
530.00	-26599.24	-25.153
535.00	-27103.46	-24.314
540.00	-27612.41	-23.416
545.00	-28126.10	-22.460
550.00	-28644.51	-21.443
555.00	-29167.67	-20.364
560.00	-29695.55	-19.221
565.00	-30228.17	-18.013
570.00	-30765.52	-16.739
575.00	-31307.61	-15.397
580.00	-31854.43	-13.985
585.00	-32405.98	-12.502
590.00	-32962.26	-10.947
595.00	-33523.28	-9.317
600.00	-34089.03	-7.612
605.00	-34659.52	-5.830
610.00	-35234.74	-3.968
615.00	-35814.69	-2.027
620.00	-36399.38	-0.003

NEAREST SPHERE - RADIUS -5.2985104D 03 MM   CURV.-1.8873229D-04

APPENDIX B

SECONDARY MIRROR SAG TABLES

PERKIN-ELMER

ASPHERIC SAG TABLE

LST RAUL 09.48.43 03/19/73

A=-1.254750D 00 B= 0.0 C= 0.0 D= 0.0 E= 0.0

CURV. -7.5518869D-04 CURV. SUBTRACTED -7.4978692D-04 SCALING FAC. 1.000

RADIUS(MM) -0.1324172D 04 SUBTRACTED RADIUS(MM) -0.1333712D 04

SURFACE NO. 2

SCALED ASPHERIC COEFFICIENTS
A=-1.254750D 00 B= 0.0 C= 0.0 D= 0.0 E= 0.0

H(MM)	SAG(MICRONS)	SUB SAG (MICRONS) relative to Nearest sphere.
0.0	0.0	0.0
1.00	-0.38	-0.003
2.00	-1.51	-0.011
3.00	-3.40	-0.024
4.00	-6.04	-0.043
5.00	-9.44	-0.067
6.00	-13.59	-0.097
7.00	-18.50	-0.132
8.00	-24.17	-0.172
9.00	-30.58	-0.218
10.00	-37.76	-0.269
11.00	-45.69	-0.325
12.00	-54.37	-0.386
13.00	-63.81	-0.453
14.00	-74.01	-0.525
15.00	-84.96	-0.602
16.00	-96.66	-0.684
17.00	-109.12	-0.771
18.00	-122.33	-0.862
19.00	-136.30	-0.959
20.00	-151.03	-1.061
21.00	-166.51	-1.168
22.00	-182.74	-1.279
23.00	-199.73	-1.395
24.00	-217.47	-1.516
25.00	-235.97	-1.641
26.00	-255.22	-1.771
27.00	-275.23	-1.905
28.00	-295.99	-2.044
29.00	-317.51	-2.186
30.00	-339.78	-2.333
31.00	-362.81	-2.485
32.00	-386.59	-2.640
33.00	-411.12	-2.799

34.00	-436.41	-2.962
35.00	-462.45	-3.128
36.00	-489.25	-3.298
37.00	-516.80	-3.472
38.00	-545.11	-3.649
39.00	-574.16	-3.830
40.00	-603.98	-4.014
41.00	-634.55	-4.200
42.00	-665.87	-4.390
43.00	-697.94	-4.583
44.00	-730.77	-4.778
45.00	-764.35	-4.976
46.00	-798.69	-5.177
47.00	-833.78	-5.380
48.00	-869.62	-5.585
49.00	-906.21	-5.792
50.00	-943.56	-6.001
51.00	-981.67	-6.212
52.00	-1020.52	-6.424
53.00	-1060.13	-6.638
54.00	-1100.49	-6.854
55.00	-1141.61	-7.070
56.00	-1183.47	-7.288
57.00	-1226.09	-7.506
58.00	-1269.46	-7.725
59.00	-1313.59	-7.945
60.00	-1358.47	-8.165
61.00	-1404.09	-8.386
62.00	-1450.48	-8.606
63.00	-1497.61	-8.826
64.00	-1545.49	-9.046
65.00	-1594.13	-9.266
66.00	-1643.52	-9.484
67.00	-1693.66	-9.702
68.00	-1744.55	-9.919
69.00	-1796.20	-10.134
70.00	-1848.59	-10.348
71.00	-1901.74	-10.561
72.00	-1955.64	-10.771
73.00	-2010.29	-10.980
74.00	-2065.68	-11.186
75.00	-2121.84	-11.390
76.00	-2178.74	-11.591
77.00	-2236.39	-11.789
78.00	-2294.79	-11.984
79.00	-2353.94	-12.175
80.00	-2413.84	-12.363
81.00	-2474.50	-12.547
82.00	-2535.90	-12.727
83.00	-2598.05	-12.903
84.00	-2660.95	-13.074
85.00	-2724.60	-13.241

86.00	-2789.00	-13.402
87.00	-2854.15	-13.558
88.00	-2920.05	-13.709
89.00	-2986.70	-13.854
90.00	-3054.09	-13.993
91.00	-3122.24	-14.126
92.00	-3191.13	-14.252
93.00	-3260.78	-14.371
94.00	-3331.17	-14.484
95.00	-3402.30	-14.589
96.00	-3474.19	-14.686
97.00	-3546.82	-14.775
98.00	-3620.21	-14.857
99.00	-3694.34	-14.930
100.00	-3769.21	-14.994
101.00	-3844.84	-15.049
102.00	-3921.21	-15.095
103.00	-3998.32	-15.131
104.00	-4076.19	-15.158
105.00	-4154.80	-15.174
106.00	-4234.16	-15.180
107.00	-4314.26	-15.175
108.00	-4395.11	-15.159
109.00	-4476.70	-15.132
110.00	-4559.04	-15.092
111.00	-4642.13	-15.041
112.00	-4725.96	-14.978
113.00	-4810.54	-14.902
114.00	-4895.86	-14.813
115.00	-4981.93	-14.710
116.00	-5068.74	-14.594
117.00	-5156.29	-14.464
118.00	-5244.59	-14.320
119.00	-5333.64	-14.161
120.00	-5423.42	-13.987
121.00	-5513.95	-13.798
122.00	-5605.23	-13.593
123.00	-5697.25	-13.372
124.00	-5790.01	-13.134
125.00	-5883.51	-12.880
126.00	-5977.76	-12.609
127.00	-6072.75	-12.321
128.00	-6168.48	-12.014
129.00	-6264.95	-11.690
130.00	-6362.17	-11.347
131.00	-6460.12	-10.985
132.00	-6558.82	-10.604
133.00	-6658.26	-10.203
134.00	-6758.44	-9.782
135.00	-6859.36	-9.340

136.00	-6961.03	-8.878
137.00	-7063.43	-8.395
138.00	-7166.57	-7.890
139.00	-7270.46	-7.363
140.00	-7375.08	-6.814
141.00	-7480.44	-6.242
142.00	-7586.54	-5.646
143.00	-7693.38	-5.028
144.00	-7800.96	-4.385
145.00	-7909.28	-3.717
146.00	-8018.34	-3.025
147.00	-8128.13	-2.308
148.00	-8238.67	-1.565
149.00	-8349.94	-0.796
150.00	-8461.95	-0.001

NEAREST SPHERE - RADIUS -1.3337123D 03 MM CURV.-7.4978692D-04